

PUMPING SPEED AND ION ASSISTED DEPOSITION

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Abstract

Common ion sources and ion assisted deposition (IAD) are briefly reviewed. Some definitions of pumping systems and vacuums are covered and the measurement of pumping speed is discussed. The interactions of ion sources with pumping speed are illustrated, and recommendations for improved IAD are provided.

Introduction

Ion Assisted Deposition is a valuable addition to optical thin film coating processes. IAD densifies a film while it is being deposited. The film quality is affected by the chamber pressure. The chamber pressure is affected by the pumping speed of the system and the gas flow needed by the ion source for a given drive/discharge voltage and current. The geometry of the ion source affects the gas flow needed to produce a given effect. This article addresses these relationships and is meant to aid in decisions related to these processes.

Pumping and Vacuum

What is a vacuum pump? A vacuum pump is a device that removes gas molecules from a selected volume. One way of describing the act of pumping is to look at the surface area in the interior of a volume (the vacuum chamber) from which the gases are removed. This is an area upon which gas particles (molecules/atoms) impinge and are “permanently” removed from the volume around it. The area might accomplish this by being a surface area, which is cold enough to freeze or chemically reactive enough to trap or “getter” any particle that comes in contact with it. A cryopump, Meissner Trap, or various other entrapment pumps behave in this fashion. The trapping effectiveness depends on the volume of gases and their freezing and boiling temperatures, relative to the collection surface temperature. The pumping area might also be an aperture, such as a hole in the outer wall of a spacecraft traveling in space, through which an interior particle would pass and never return. A whole family of pumps referred to as transfer pumps behave in this fashion.

In cases where there are no significant gases coming backward from the collection area, the pumping speed (PS) of the

area can be calculated, and it depends on the size of the area. Roth^[1] shows that the PS in liters per second (L/s) in such cases is 11.6 times the area in cm² as shown in Equation 1.

$$PS (L/s) = 11.6 * A(\text{cm}^2) \quad (1)$$

For example, a 10 cm diameter aperture would have a PS of 911 L/s and a 20 cm aperture would have four times that or 3644 L/s. Any obstructions in this area or passageways leading to it would reduce the “conductance” and thereby reduce the effective net PS of the combination. A method to assess the approximate PS of a system is to pump the volume to a low pressure and then admit a controlled flow of a known gas such as argon, and observe the pressure in the chamber. If the gas flow is measured in standard cubic centimeters per minute (SCCM) and the pressure in Torr, then the PS can be estimated by Equation 2.

$$PS(L/s) = 0.0127 * SCCM / \text{Pressure(Torr)} \quad (2)$$

Mean Free Path

The mean free path (MFP) is the statistically averaged distance that a gas particle will travel before having a collision with another particle as a function of chamber pressure (P). MFP is given by Equation 3.

$$MFP(\text{cm}) = 5 \times 10^{-3} / P(\text{Torr}) \quad (3)$$

This is discussed more extensively by Willey^[2], but a key point is that, at a distance of one MFP, only 1/e or 36.8% of the particles have *not* had a collision. (Euler’s number $e \approx 2.718281$). Figure 1 illustrates this. It can be observed that, after travelling only one tenth (0.1) of the MFP, a particle has a ~90% chance of not having a collision. Therefore, the distance from an evaporation source or ion source to a substrate would need to be on the order of 0.1 MFP in order for collisions to not be a major factor in the process. For a distance, this implies that the pressure needs to be 5×10^{-6} Torr. Collisions with ions from a source with a background gas will negate “line-of-sight” travel, cause loss of energy/momentum of the ion, and cause charge transfer to non-accelerated ions.

The MFP is also a function of temperature and the diameter of the specific particles involved, but Equation 3 will be used as a working approximation. The residual gas particles in the

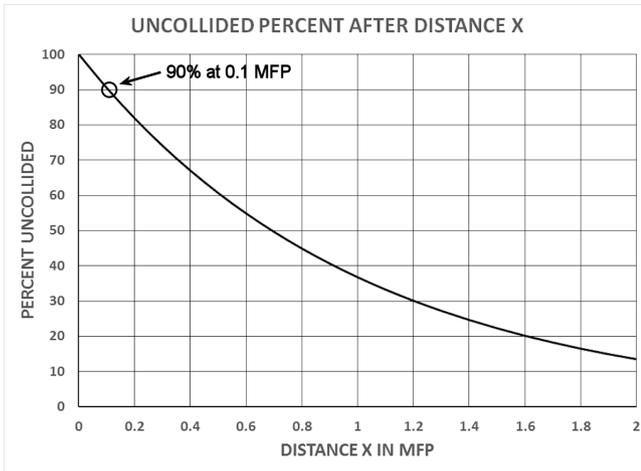


Fig. 1 Percent of atoms/molecules that have collided after travelling a fraction of the mean free path (x).

chamber also have significant interactions with the depositing material particles of the optical film. Excess residual gas is known to cause deposits to be less dense. The coating density is a function of background gas ratio. The amount of background gas collisions affects the arrival rate and depositing particle density.

Ion Assisted Deposition

Ion sources bombard a depositing film with energetic ions of argon, nitrogen, oxygen, or other elements. These ions have several beneficial effects on the film such as densification, oxidation, adhesion, and compound synthesis. The three most significant ion properties include the energy in electron volts, the ion-to-atom-arrival-rate (IAAR), and the mass/momentum of the gas particles. The gas fed into the ion source is ionized by collisions with electrons and the ions are accelerated away from the ion source by repulsion from an anode surface at a given voltage. The rate of ion flow and the voltage or current (indirectly) are determined by the SCCM of the gas provided to the ion source.

There are a variety of ion sources in use today. Five such sources are considered here, which have sufficient data available to make reasonable comparisons. These are the Mark II^[3], EH400 and EH1000^[4], ST55^[5], and Fafnir^[6]. These are all essentially “End Hall” gridless sources. Their behaviors are similar but vary to some degree due to differing geometric features. More details can be found in Reference 2.

Effects of Pumping Speed

One of the points of this article is to show the effects of the PS of the chamber on the IAD contribution to the process of the system in which the ion source is employed. Figure 2 compares the drive voltage (V_d) versus chamber pressure and PS of the various ion sources. The MK-II, EH400, and EH1000 have very similar geometries and show similar performance except for scale. The available data ranges are from 3 to 4 drive amps.

The EH400 curves are shown for two chambers with pumping speeds of 800 and 1100 L/s, as provided by the manufacturer’s manual. It can be observed that the pressure drops for a given drive voltage with increased PS, or alternately the drive voltage drops at a given pressure with increased PS. The larger model, the EH1000, shows similar behavior. The dashed MK-II curve at 2500 L/s and 4 amps is similar to the EH1000 at 3A and 800 L/s. However, the MK-II at 3A and 7000 L/s is far to the left in Fig. 2, showing the dramatic effects of higher PS. The Fafnir source has somewhat similar performance to the MK-II and EH1000, except that the effects of its differences in geometry can be seen. The most different source from these others is the Saintech ST55 seen to the left in Fig. 2 with 3A and 2000 L/s. The ST55 power supply has five discrete selectable drive voltages represented by the large dots connected by the line with small dashes in Fig. 2. The drive current can be varied continuously by controlling the SCCM and filament current of the ST55.

Likely Process Effects of Pumping Speed

Westwood^[7] reported a study of the energy lost due to collisions as a function of pressure. He showed that energetic argon atoms colliding with other ambient argon atoms are expected to retain a residual energy (RE) of only about 40% of their initial energy. This could be expressed by Equation 4, where n is the number of MFPs travelled.

$$RE = \sim(0.4)^n \quad (4)$$

Therefore, after some number of collisions (such as 5 or more), the atom would become “thermalized.” That is, it would have no more energy than those atoms which had not been energized. This approximation can then be used to estimate the percent of residual energy that might reach a substrate at a distance such as 50 cm from the ion source, based on the number of MFPs (collisions) in 50 cm distance at any pressure, P . Equation 5 provides this estimate and is plotted as a dot and dashed line in Fig. 3.

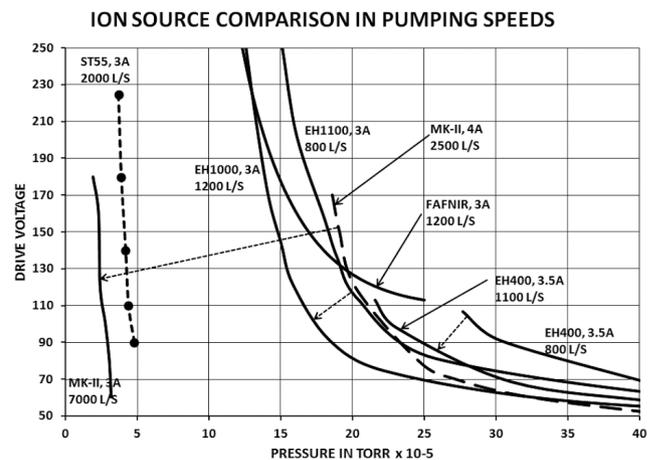


Fig. 2 Comparison of the drive voltage (V_d) versus chamber pressure and pumping speed of the various ion sources.

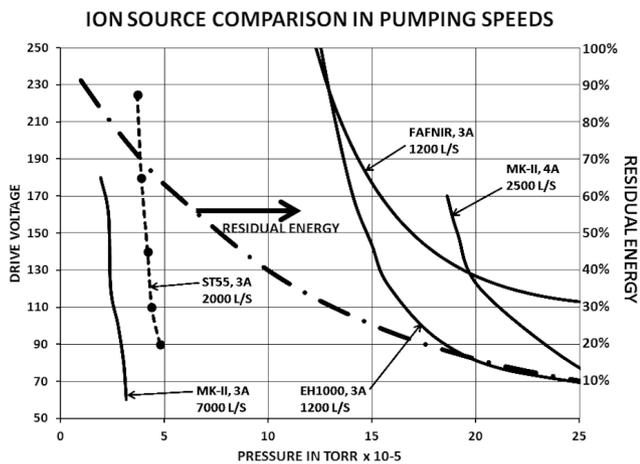


Fig. 3 Comparison of the percentage of residual energy of ions versus chamber pressure and pumping speed for various ion sources. Also shown are the drive voltage versus pressure and pumping speed for various ion sources.

$$RE(P) = 0.4^{(P \times 10^4)} \quad (5)$$

Each of the sources and conditions seen in Figure 3 are expected to have almost all of the ions encounter some collisions and lose some of their energy before reaching the substrate. The two cases to the left of Fig. 3 have a majority of ions that have not collided before they reach the substrate, whereas those to the right have had many collisions. The different effects of these two classes of IAD are expected to have significant influence on the properties of the coatings produced.

An ion of specific RE would arrive at the coating surface and compete for a position with other particles in the growing coating. The ion would collide with atoms of the depositing material and transfer much of its energy to those atoms. That energy would allow the depositing atoms to retain some mobility and to migrate further into denser packing positions before that energy would be lost by conduction to the surrounding materials. This energy or heat can have influences like annealing, similar to those of a heated substrate. This in turn would affect the packing density of the film and its crystallization state, which would vary from one material to another.

Sainty¹⁰ demonstrated the benefits of IAD in the deposition of TiO₂ in a lower pressure regime such as this, and that is consistent with the above conjectures.

Zdunek, et al.⁹, described a special pulsed gas sputtering process in which “a higher free path of the gas (plasma) should result in a smaller loss of kinetic energy of particles. This is caused by mutual collisions due to increased free path of the particles in comparison to the standard condition for magnetron sputtering. One of the most spectacular effects of the solution is that the coatings become denser with very good adhesion to the substrates, even in non-heating condition during the deposition process.” The present work is also consistent with the goals reported by Zdunek.

Conclusions

The benefits of IAD to a particular film deposition depend on the requirements, materials, conditions, and deposition system. Each case needs to be addressed individually and optimized with respect to its needs. It has been shown that there are potentially a wide range of pressures, ion voltages, and currents that can be employed for IAD. The author tends to prefer lower pressures to promote greater deposition density, and concludes that higher pumping speeds are desirable. Lower drive voltages are also desired to avoid dissociation of molecules into their elemental components, such as the separation of the magnesium from the fluorine in MgF₂, which causes absorption^[10]. This further justifies the benefits of higher pumping speeds.

Reference

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About the Author Ron Willey



Ron Willey graduated from MIT in optical instrumentation, has an M.S. from Florida Institute of Technology, and over 50 years of experience in optical system and coating development and production. He is very experienced in practical thin films design, process development, and the application of industrial design of experiments methodology. He is the inventor of a robust plasma/ion source for optical coating applications. He worked in optical instrument development and production at Perkin-Elmer, Block Associates, United Aircraft, Martin Marietta, Opto Mechanik, Hughes and formed Willey Corp., which serves a wide variety of clients with consulting, development, prototypes, and production. He has published many

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