# Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD) System For Volume Production of Thin-Film Coatings

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## ABSTRACT

An innovative Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD) system has been developed for low temperature, high volume production of thin-film coatings. The IFCAD system employs electro-magnetic and mechanical filtering techniques to remove unwanted macro-particles and neutral atoms from the plasma stream. Therefore, only ions within a defined energy range arrive at the substrate surface, depositing thin-films with excellent mechanical and optical properties. Ion-Assisted-Deposition (IAD) is coupled with Filtered Cathodic Arc (FCA) technology to enhance and modify the arc deposited thin-films. Using an advanced computer controlled plasma beam scanning system, high quality, large area, uniform IFCAD multi-layer film structures are attained. Amorphous Diamond-Like-Carbon (A-DLC) films (up to 85% $sp^3$ bonded carbon; and micro-hardness greater than 50 GPa) have been deposited in multi-layer thin-film combinations with other IFCAD source materials (such as: $Al_2O_3$) for optical and tribological applications. The new IFCAD technology has been included in development programs, such as: plastic and glass lens coatings for optical systems; wear resistant coatings on various metal substrates; and ultra smooth, durable, surface coatings for injection molds.

## INTRODUCTION

The new manufacturing prototype Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD) system consists of a cylindrical rotary deposition chamber, orientated horizontally, and two (or four) Filtered Cathodic Arc (FCA) sources each associated with an end-Hall Ion-Assisted-Deposition (IAD) ion gun. Since Silicon (Si) does not arc well due to its semi-conductor material property, the system is also equipped with a special Ion-Assisted-Deposition (IAD) $SiO_2$ source. By coupling Ion-Assisted-Deposition (IAD) with FCAD, in this new production prototype chamber, the development of cost effective deposition processes for applying super hard advanced thin-film materials such as: Amorphous Diamond-Like-Carbon (A-DLC); Aluminum Oxide ($Al_2O_3$); Aluminum Nitride (AlN); Carbon Nitride ($C_3N_3$); Titanium Nitrite (TiN); Titanium Nitride Carbide (TiCN); Titanium Oxide ($TiO_2$: Rutile); and many others are now feasible. IAC's advanced Ion-assisted Filtered Cathodic Arc Deposition (IFCAD) system is projected to provide a unique solution to many historical hurdles encountered in laboratory versions of FCAD technology. In addition, the new IFCAD system is designed to have the ability to deposit A-DLC, amorphous $Al_2O_3$, and many other materials in multi-layer thin-film structures suitable for tribological and electro-optical applications. The film properties produced by IFCAD technology are superior to other processes at elevated deposition temperatures, for example: the A-DLC thin-films have a micro-hardness in excess of 50 GPa (Diamond = 100 GPa); and the amorphous $Al_2O_3$ films have a hardness in excess of 20 GPa (bulk sapphire is 35 GPa). The new IFCAD system is ultimately designed to be an enabling technology for many novel commercial, military, and space applications.

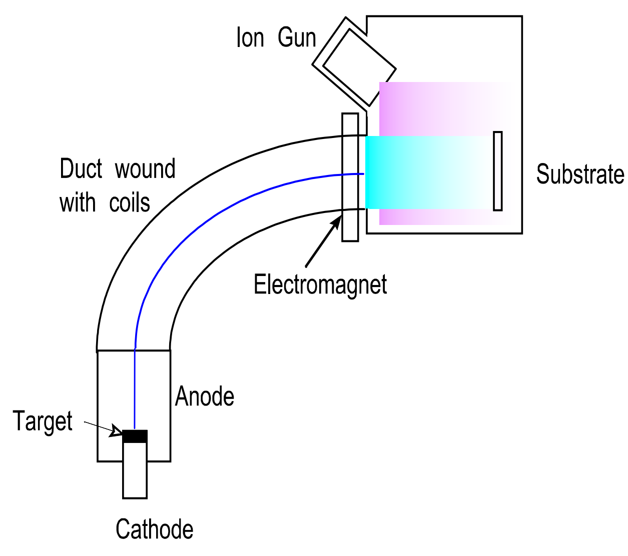


Figure 1. Schematic view of the IFCAD technology.

As presented in the schematic, the self-sustaining arc is produced in the water-cooled cathode block by a conventional arc welding power-supply (no high voltage required!). Carbon ($C^+$), Aluminum ions ($Al^+$), or other materials are ejected from the metal arc-target and magnetically steered out of the duct, while a mechanical filter captures the undesired macro-particles and neutrals. As the ejected ions emerge from the duct, an oscillating electromagnetic field scans (or sweeps) the plasma-beam to provide a uniform deposition over the substrate area. Simultaneously, a beam of gas ions, from an end-Hall ion source, impinges on the arriving arc-generated ions, resulting in dense, well-adhered, stable thin-films. This deposition process is done <u>at room temperature!</u>

**TECHNOLOGY BACKGROUND**

More than a century ago Thomas Edison produced coatings using a vacuum arc. Nevertheless, only in the last decade has arc technology penetrated commercial markets, particularly in the coating of machine tools with metal nitrides to extend their lifetimes. Arc technology has an important potential role to play in the development of electronic material quality thin-films because FCAD produces highly ionized atoms that are deposited on the substrate within a controlled energy range. [1]

A small number of research institutes, and a few industrial companies, have investigated filtered cathodic arc deposition for several years. Early research work concentrated on the unique material properties of thin-films deposited using this method. Historically, carbon has received most of the research attention. Aluminum Oxide ($Al_2O_3$), and other materials like TiN, have more recently underwent serious laboratory investigation. The earliest studies found that the FCAD thin-film properties were highly dependent on the ion energy (usually controlled by applying a substrate bias). Additionally, it was found that these films were rendered less useful by the high density of particles adhering to the deposited coating. The, so-called, "macro-particles" were generated simultaneously with the FCAD ions, and could not be removed completely by early filtering system designs. [2-3]

Further work, therefore, concentrated on improving the removal of the macro-particles. New filtering techniques were investigated and the resultant reduction in macro-particles started to produce coatings that could be used in a number of critical applications. The new filtering designs involved changing the angles of the duct bend, increasing the substrate-to-target distance, and improving the mechanical filters. [4]

The most notable recent commercial application for this technology is the coating of razor blades. Gillette has patented a specific version of the Filtered Cathodic Arc dedicated to depositing Amorphous Diamond-Like-Carbon (A-DLC) on the blades used in their new triple blade shaving system (Mach3™). [5] This gives impetus to the notion that there is whole host of other thin-film applications suitable for FCAD technology.

**Historical Drawbacks to Filtered Cathodic Arc Deposition**

Even though recent research effort has concentrated on producing clean thin-films, with excellent mechanical and optical properties, much remained to be done to develop the Filter Cathodic Arc Deposition technology into a commercially useful technology. The following summarizes some of the technical problems that have plagued the FCAD science for past few years:

(1) Control and reliability of the process was a serious obstacle to commercializing the FCAD technology. Deposition rates, although quite high (up to 5.0 nm/s), were often erratic. Predominantly, this was due to the arc-spot wandering randomly over, and sometimes off, the target material. It was a usual practice, during FCAD processes, to manually strike the arc, and then have the operator monitor it quite closely throughout the deposition. In addition, the arc-spot tends to erode one particular place on the target surface, exacerbating the control problem.

(2) Uniformity of the FCAD over distances greater than a few inches had been difficult to achieve. Typically, a magnetic coil placed at the exit of the bend would deflect the ion beam—a simple electromagnetic polarity change was used to sweep, or scan, the ions onto the substrate surface. However, the variation in the thickness across the substrate was not precisely controlled.

(3) Deposition of multi-layer materials has not been investigated in any significant way. Most FCAD systems have used only one arc source, which meant that only one material could be used to deposit a thin-film. However, most optical coatings require the deposition of at least two materials. In addition, it has been shown that FCAD doesn't deposit all materials well, and indeed cannot deposit materials with high electrical resistance (such as silicon). This restriction has severely limited the historical usefulness of FCA for some applications, particularly in optics.

(4) Co-deposition of materials is also required in advanced thin-film applications. Even though deposition by two separate FCAD sources, running simultaneously, has been attempted, the interaction between the two often led to uncontrolled properties in the composite film. This effect was largely due to the close proximity of the two sources, creating interference between the adjacent magnetic fields.

(5) Anode caking and poisoning has been another major historical drawback. During the FCAD process a large

amount of target material is ejected as molten droplets (or particles, in the case of materials like carbon). These particles readily adhere to the anode and can arrest the arc process by increasing the 'resistance' between the anode and cathode. Typically, the adhered target material must be mechanically scrapped off of the anode during maintenance; however, some material adheres extremely well, and cannot be removed. If the FCAD process is used to deposit materials, such as Aluminum Oxide (by converting aluminum within an oxygen background), the anode becomes coated with an insulating layer of $Al_2O_3$ material that will disrupt the process.

**New Advanced Ion-assisted FCAD (IFCAD) System Design**

Coupled with Ion-Assisted-Deposition (IAD), the advanced IFCAD (featuring a custom designed particle-free filtration) has a particularly important role to play in the advancement of electro-optical material science. Empirical evidence has confirmed that IAD substantially improves thin-film properties when compared to conventional Physical Vapor Deposition (PVD). In summary, it has been demonstrated that bombardment of a growing film with energetic ions enhances the performance of the thin-films: Improved film adhesion is achieved by ionic bombardment of the substrate prior to film deposition. Densification of the film, deposited on either heated or unheated substrates, is achieved with IAD. Other film properties are positively influenced by this technique, such as: residual stress modification; surface morphology structures (crystal orientation, smoothing, and grain size); enhanced electro-optical performance (stable refractive index and low-absorption); and durability. [6-9]

Therefore, the new IFCAD deposition system is designed, by coupling IAD into the process, to eliminate most of the historical problems that have impeded the development of FCAD into a complete production technology. The following are some of the innovations that have been incorporated into the design of the new IFCAD system:

(1) It is now possible to control the FCAD process more reliably by using feedback from sensors to initiate and maintain a more consistent output from the FCA source. Monolithic photo diodes are used to measure the light intensity of the arc-plasma from various locations in the system. This feedback control system is designed to maintain a reliable deposition rate. In addition, the monitoring system will adjust the position of arc initiation over most of the target area resulting in uniform erosion of the surface.

(2) By employing a complete integrated magnetic control circuit design (powered by a computerized waveform generator) the deflection of the plasma ion beam is much more linear. The combination of one beam-scanning axis with a second substrate rotational axis results in the ability to uniformly coat large, complex, substrate surfaces. In addition, the prototype system can accommodate up to four individual FCAD sources, permitting the coating of significantly larger substrates than any single source system.

(3) The new innovative system has provision for a thermal evaporator, or e-beam gun, as well as the four FCAD sources. Design flexibility allows for the port positions in the system to hold either FCAD or end-Hall ion-beam sources. The system's versatility provides for the development of advanced deposition processes, for high performance coatings, by permitting wide latitude in the selection of the best source and location for each thin-film material.

(4) FCAD sources can be placed on either side of the chamber to allow the deposition of materials simultaneously with minimal magnetic field interference between the two. The substrate holder effectively acts as a shield between the sources—preventing deleterious magnetic interaction.

(5) Anode poisoning is greatly reduced by the novel use of Ion-beam Assisted Deposition (IAD). The reactive gas is directed toward the substrate, reducing the amount of insulating material in the anode area. Additionally, an innovative protective shield, made from either graphite or aluminum, is used to protect the actual anode from being poisoned by target material.

**Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD) System Summary**

Much like IAD technology in the 1970's, FCAD has been confined to the realm of academic and laboratory investigations. Building on this pioneering experience, with the gridless end-Hall ion source for optical coating applications, a similar scenario is being pursued for the commercialization of the IFCAD technology:

The new prototype Ion-Assisted Filtered Cathodic Arc Deposition (IFCAD) coating system consists of a cylindrical rotary deposition chamber, orientated horizontally, incorporating up to four Filtered Cathodic Arc (FCA) sources and an special Ion-Assisted-Deposition (IAD) $SiO_2$ source. Aluminum Oxide ($Al_2O_3$) in combination with other materials, such as: Amorphous Diamond-Like-Carbon (A-DLC); refractory metals; metal oxides; compounds and alloys of such materials can be deposited onto various types of substrates. The deposition process involves rotating a large area cylindrical substrate holder, mounted with a variety of possible geometric substrate configurations (consisting of either metals, semiconductors, plastics, ceramics, or glass), past the FCA sources that sweep an uniform beam of deposition ions onto the rotating substrates. The FCA sources, in separate, sequential, or simultaneous depositions, synthesize a broad range of materials, at ambient temperature. Extremely durable advanced electro-optical thin-film materials, of nominal dielectric constants, will be reliably produced with a controlled uniform coating thickness.

Central to this innovative design, as compared with previous systems, is the ability to deposit multi-layer combinations of advanced electro-optical materials onto temperature-sensitive substrates. The quality of the Aluminum Oxide film, for example, produced by this FCA technology, is expected to exceed other $Al_2O_3$ films deposited at elevated temperatures in terms of hardness, Young's Modulus, density, dielectric constant, and surface smoothness. The cylindrical rotating geometry used in the system design will provide for high rate, uniform deposition of quality coatings, ideally suited for advanced tribological and electro-optical applications.

The IFCAD source, as depicted in the Figure 1, uses a low DC voltage (high current) supply to generate an arc on a water-cooled target. The "self-sustaining" arc vaporizes the target material generating high-energy ions, neutral atoms and particles. Ejected target ions are steered by the magnetic and electrical fields through a curved duct. A mechanical "non-line-of-sight path" filter traps the particles and neutrals leaving only a pure beam of ions to enter the chamber. Since the only heat generated by this process resides in the water-cooled cathode assembly (external to the chamber), the substrate remains close to room temperature during the thin-film deposition.

The plasma beam (ions) is horizontally scanned at the exit of the duct using an electro-magnetic field controlled by a computerized waveform generator. Analogous to brush painting, the ion beam is swept side to side to uniformly coat the substrate. A sizeable deposition width will be obtained: typically greater than ten inches. When the substrates are mounted on a rotating drum, or on an in-line translation stage, then a significant volume of components can be coated efficiently at low cost. In addition, the emerging ions can be accelerated (or slowed) by either applying a RF or DC substrate bias (depending on the substrate's electrical conductivity), permitting accurate control over the energy of the arriving ions. These process controls result in well-adhered, dense, uniform, and stress controlled thin-film coatings. The deposition rate for $Al_2O_3$, or Carbon, is greater than 5 nm/s per $in^2$, which compares favorably to most other conventional deposition technologies.

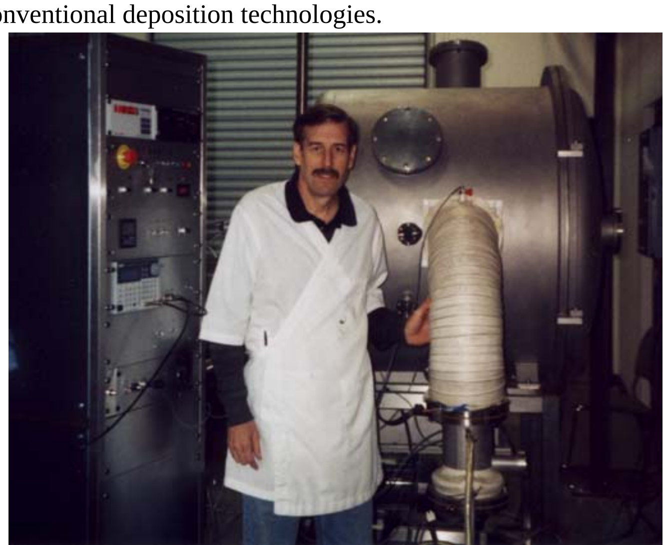

Figure 2. Photograph of the IFCAD system

**CONCLUSION**

The ability to use this new IFCAD system for multi-layer production coatings hinges on the advanced film properties achieved. Carbon, for example, has been one of the most interesting materials deposited using FCAD. Nanoindentation, scratch test, fretting test, EELS, Raman, UV/VIS/IR spectroscopy, and surface profilometery have been used to characterize the Amorphous Diamond-Like-Carbon (A-DLC) produced by FCAD.[10] The thin-film properties of A-DLC are summarized in Table I.

Table I. Amorphous-DLC Film Properties

| **Property** | **Value** |
|---|---|
| Hardness | > 50 GPa |
| Young's Modulus | > 500 GPa |
| Coefficient of Friction | < 0.15 |
| Critical Load | > 5mN |
| Percentage of $sp^3$ Content | > 80% |
| Plasmon Peak Position | > 30 eV |
| Density | > 3.25 $g/cm^3$ |
| Stress | ~ 6-10 GPa |
| Refractive Index | ~ 2.6 |
| Optical Bandgap | ~ 2.0 eV |

Using these superior properties of the A-DLC in multi-layer combination with other IFCAD materials provides the thin-film practitioner a broad new set of possible coating strategies for advanced electro-optical applications. The new IFCAD system offers a new and powerful method for the future volume production of advanced thin-film multi-layer coatings at room temperature.

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