Many of the studies on the effect of magnetic fields on electrons in vacuum were done in developing vacuum gauges beginning in about 1898 [0]. Devices that use magnetic fields to control the motion of electrons are called magnetrons. GE coined the term magnetron in the early 1920s when they were studying the use of magnetic fields instead of grids in electron tubes because of the vulnerability of their patent position on grid-controlled electron tubes [1].

In the mid-1930s Berkhart and Reineke patented a means of increasing the ionization of atoms thermally evaporated into a plasma at low pressure [2]. They used a magnetic field parallel to the electric field between the source (anode or ground) and the substrate (cathode). This was the first attempt to cause post-vaporization ionization in PVD processing. Their patent was assigned to Bernhard Berghaus, who had a patent on an early version of "Ion Plating" using both thermal evaporation [3] and sputtering [4]. The work of Berghaus was not pursued apparently from the lack of interest in what are now called "metallurgical coatings." Burghaus did pursue the work that he and Arthur Rudolph Berthold Wernelt had done on what is now called "ionitriding" (German patent 668,532 [1932]*). (Ionitriding, and other plasma surface treatments are used in duplex coatings involving PVD [5,6].)

In 1939 F.M. Penning patented the deposition of material by sputtering (he called it "cathode disintegration") using a cylindrical magnetron configuration ("Penning cell") with designs where the magnetic field was both parallel and perpendicular to the cathode surface [7,8]. In one configuration the cathode is a rod (or post) centered in a cylinder (anode), and the magnetic field was parallel to the rod and was thus perpendicular to the electric field (i.e. post cathode or cylindrical magnetron sputtering design). The motion of the electrons emitted from the cathode was such that they circled the cathode as they moved toward the ends of the rod due to drift normal to the EXB plane. The confining of the electrons and increased their path length and increased the current density and as Penning said "made the pressure appear to be higher" (as compared to the current without the magnetic field). Sputtering takes place from the surface of the post. Penning noted that the "cathode particles disintegrated combine with gas molecules and thus bring about a reduction in pressure." Penning pointed out that the establishing and maintaining of a glow discharge was due to the confinement of the electrons by the magnetic field [9].

In the Penning's cylindrical cathode the electrons are lost at the ends of the cathode. By adding flanges ("wings") to the ends of the post ("spool" design) the electrons can be further confined to the cathode surface. In another configuration the cylinder is made the cathode while the post (or end plates) is the anode ("inverted" or hollow-cathode magnetron). The sputtering then takes place from the interior surface of the cylinder. Interior flanges on the ends of the cylinder help confine the electrons.

Much of the early work on developing the post magnetron sputtering configurations for film deposition was done by Allan Penfold and John Thornton at Telic Corporation in the early 1970s [10]. More recent work has been done by David Glocker, particularly on the inverted magnetron designs [11]. A variation of the inverted-cylindrical configuration uses a conical shaped cathode ("S-gun") with an anode at the small end [12**].

Penning's 1939 patent also discussed the use of a DC magnetron sputtering in what is now called a "sputter ion pump" a type of "getter" or "capture" pump where the sputter deposited film is used to react with reactive gases and to "bury" inert gases [14]. Ion pumps were the first large commercial use of magnetron sputter deposited films. There were many early developments in the sputter ion pump including W.F. Westendorp and Anatole M. Gurewitsch, USP 2,755,014 (1953), L.D. Hall USP 2,993,638 (1961), and Wolfgang Knauer USP 3,216,652 (1965).

Knauer's patent is interesting in that he used permanent magnets inside the post cathode to give an emerging re-entry magnetic field that produced closed electron paths (rings) around the post cathode ("closed-field"). Knauer also described a planar magnetron, which created a closed circular plasma path (washer-shaped) on a planar surface for sputtering (Fig. 2 of his patent) [15,16]. Knauer studied the sputter erosion path on a planar surface in a Penning cell [17]. (Eric Kay wrote a seminal paper on magnetic field effects on glow discharges as understood in 1963 [18].)

DC diode magnetron sputtering configurations using emerging/re-entering magnetic fields on the cathode surface began to be important in PVD film deposition in the early 1970s. Mullaly (DOE DOW Chemical Rocky Flats Plant (RFP)) used a hemispherical quadrupole magnetic field configuration to sputter from the interior surface of a hemispherical cathode [19]. John Chapin (Vacuum Technology Associates (VTA)***) took the hemispherical configuration elongated it into a trough shape and then flattened it out to give a "closed field" planar magnetron using permanent magnets. This magnetron design gave an elongated "racetrack" of plasma on the planar surface created by the electron drift normal to the EXB plane [20]. This work was done under a development contract with Airco, which led to prolonged litigation over the

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* In 1939 Berghaus fled Nazi Germany and went to Switzerland carrying all his research notes. Apparently he never tried to patent, publish or commercialize his knowledge on PVD. Berghaus died in the early 1960's and the Klockner Group AG of West Germany bought his research notes from his estate. The West German government funded an R&D program into plasma-surface interactions that led to the further development of plasma nitriding ("ionitriding") that is widely used to hardened metal surfaces.

** Note: On Peter Clarke's patent the name is spelled Clark, which has been the source of some erroneous references.

*** Chapin had worked at the Rocky Flat (RFP) DOE facility and was one of those who left RFP to form Vacuum Technology Associates (VTA). Mullay's work at RFP was probably not patented since all work done at GOCO laboratories was in the public domain at that time (Donald M. Mattox, SVC Bulletin Editorial "Patent Law redux" [Spring 2011]).
manufacturing/sales rights between Airco and VTA [21]. Chapin’s patent application was preceded by one from Corbani [22] but Chapin was able to “swear behind” Corbani’s claim based on an entry in his laboratory notebook witnessed by Bob Cormia (Airco).

The DC elongated closed-field planar magnetron sputter deposition source revolutionized Web Coating [23], Large Area Rigid coating [24] and the coating of temperature-sensitive materials particularly the decorative coating of polymer auto front grilles with a chromium alloy [25]. The magnetron source had a very interesting application for in situ, in-line sputter cleaning of strip metal in roll-to-roll coating [26]. In Europe a magnetron configuration called the “Ring Gap Discharge” began to be developed and commercialized in the mid-1970s [27, 28]. Multiple “ring gap” sources could be arranged in different configurations to give linear sources or large-area sources.

Using the emerging/re-entering magnetic closed field magnetic “tunnel” electrons can be effectively trapped in a small volume. In 1986 Windows and Savvides recognized importance of letting some of the electrons escape and thus creating a plasma in the volume outside the tunnel [29]. This plasma region “activates” reactive gases/vapors and acts as a source of ions for energetic ion bombardment of the depositing coating material – they called this configuration an “unbalanced (UB) magnetron” configuration. Multiple UB magnetrons may be magnetically linked to form even larger plasma volumes [30,31].

DC magnetron sputtering works well with targets that are electrical conductors but doesn't work with electrical insulators. By applying an rf (13.56 MHz) to the cathode, insulators such as SiO$_2$ [32] and Al$_2$O$_3$ [33] may be sputtered. Rf magnetron sputtering has largely been replaced by reactive sputter deposition except for some cases of insulating materials with complex compositions.

Reactive sputter deposition involves sputtering from an elemental (e.g. Ti), alloy (e.g. Ti:Al), or other electrically conductive (e.g. ITO) target and reacting with a reactive gas (e.g. nitrogen, oxygen) or with a co-deposited material (e.g. carbon, boron) on the substrate surface. Major advances in reactive sputter deposition came with techniques to control the partial pressures of the reactive gas (optical emission spectroscopy [OES] and differentially pumped mass spectrometry) in order to limit the “poisoning” of the target surface and the attendant reduction in sputtering rate [34-38]. A problem with reactive sputtering is arcing on the target surface from the “poisoning” by reaction. This can be overcome using rf or mid-frequency (MF - 50-250kHz) pulsed bipolar power supplies [39-41]****.

Dual closed-field magnetron sources may be electrically linked in a mid-frequency AC configuration so that the magnetron surfaces can alternately act as cathodes and anodes to minimize the “disappearing anode effect” in reactive sputter deposition processes due to coating of the anode by a depositing insulating layer [42-44]. (Non-magnetron low frequency (60Hz) dual cathode AC sputtering was discussed in 1971 [45].)

One disadvantage of the closed field planar magnetron sputtering configuration is the low material utilization outside the tunnel “racetrack.” Various designs have been proposed to increase material utilization [e.g. 46-51] but the most effective uses a rotating cylindrical (tube) source [52,53], which may be used in a MF dual magnetron configuration. A problem with the rotating cylindrical magnetron source is that some materials are difficult to form into long tubes that are structurally sound.

“Open drift” magnetron sputtering sources have been constructed where the magnetic field is parallel to the surface over the whole surface area and there is no closed magnetic field on the sputtering target surface [54,55]. In this configuration the plasma may be enhanced by electron emission from an electron-emitting filament along one edge of the planar surface [56].

The common planar magnetron utilizes secondary electrons from the cathode to sustain the plasma. Injecting electrons from other sources into the plasma may be used to increase the plasma density. Such electron sources may be from hot filaments [0,56] or hollow cathodes [57]. There also have been magnetron designs that are intended to create post vaporization ionization of the vaporized material (iPVD) [58,59] but these designs have been negated by the development of High Power Pulse Magnetron Sputtering (HIPIMS), which inherently gives a high degree of ionization of the vaporized material.

High Power Pulse Magnetron Sputtering (HIPIMS) utilizes very high power densities of >1kWcm$^{-2}$ in short pulses (impulses) of tens of microseconds at low duty cycle (on/off time ratio) of < 10% [60-63]. A distinguishing feature of HIPIMS is the high degree of ionization of the vaporized material (“self-ions”). Ions of the vaporized material are effective in sputter cleaning the substrate surface and for modifying the surface by subplanting atoms of the coating material into the surface prior to the deposition of the coating [64]. This is similar to the arc bonded sputtering (ABS) system where by changing the magnetic field configuration the magnetron sputtering source can be converted into a steered arc vaporization source [65].

The length of the HIPIMS pulse is determined by that needed to prevent the transition of the discharge from a glow to an arc condition on pulsing. The peak power and the duty cycle are selected so as to maintain an average cathode power similar to conventional DC diode sputtering (1–10 Wcm$^{-2}$) to allow efficient cooling. Various pulse shapes have been reported for generating the pulse power for HIPIMS [66].

The high degree of ionization of the vaporized material in HIPIMS has reignited interest the role of “self-sputtering” by “self-ions” of the vaporized material in sputtering process and in the sputter deposition process [67]. In addition to the surface preparation prior to the coating formation these “self-ions” can play an important role in tailoring the film/coating properties by energetic particle bombardment of the depositing material during the deposition process. The “self-ions” are particularly suited for transferring momentum to the deposited surface atoms since they have matching AMUs.

**Conclusion**

Magnetron sputtering is a rather mature technology [63,68] that has revolutionized the vacuum coating industry and has been an enabling technology in many areas such as tool coating, low-e coatings on architectural glass, and deposition of compounds on many thermally sensitive polymers at commercially viable unit...
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Cost. The magnetron sputtering process itself is still not completely understood as exemplified by the presentation [69]:

"Magnetron Sputtering: An Unfinished Journey"
André Anders, LBNL

Abstract
"Cathode disintegration, as sputtering was originally called, has its humble beginnings in the 19th century with ingenious inventions closely related to generating electrical power and establishing "empty space," vacuum. We celebrate Geissler and his glass chambers, Ruhmkorff’s induction coil, and Grove’s observation of coatings next to a cathode tip (1852), followed by Wright’s systematic fabrication of thin films (1877). Paving the way in the 1930s for later breakthroughs, Penning described the trapping of electrons in certain electric and magnetic field configurations, concepts leading to the development of our modern magnetrons in the 1970s (Chapin, Clarke, Penfold and Thornton). This, however, was just the beginning of an incredible success story that affects everybody’s life today as magnetron sputter deposition enabled a wide range of product developments. Different magnetron geometries (planar, rectangular, cylindrical), scaling, rotating targets, dual magnetrons, and magnetrons in hybrid configurations with other discharges expanded the availability and variety of coatings. Plasma transport and thin film growth theories laid the basis for optimization. Pulsing at radio-frequency (rf) made the use of insulating targets possible, and medium frequency (mf) pulsing, fast gas feedback loops, and fast arc suppression circuits were major advancements to minimize unwanted arcing, especially for reactive deposition conditions (early 1990s). Magnetic unbalancing brought plasma assistance to the deposition process (1980s), and pulsing at extreme peak power densities introduced plasma-deposition by HiPIMS and HiPIMS-like processes at the turn of the millennium. Yet, there are surprising features to be discovered, explained, and exploited, such as the recent (2012) observations of traveling ionization zones or “spokes”, which have profound influence on magnetron operation and particle fluxes to the substrate. The journey in the world of magnetron sputter deposition is far from finished, which becomes abundantly clear when looking at its history in a time lapse format.”

References
1. V.W. Gaede, "Tiefdruck Messungen" (low pressure measurements) Zeitschr. f. Techn. Physik 12, 664 (1934) - vacuum gauge review paper
4. "Coating of articles by cathode disintegration," Bernhard Berghaus and Wilhelm Burkhardt, USP 2,305,758 (priority (Germany), May 25, 1937; filed, April 22, 1938; published, Dec. 22, 1942)
8. F.M. Penning, "Die Glimmentladung Bei Niedrigem Druck Zwischen Koaxialen Zylindern in Einem Axialen Magnetrond, "("The glow discharge at low pressure between coaxial cylinders in an axial magnetic field") Physica 3(9) 873 (1936)
23. "History of vacuum roll coating" John B. Fenn, Ch. 3 p. 16) in 50 Years of Vacuum Coating Technology and the growth of the Society of Vacuum Coaters, edited by Donald M. Mattos and Vivienne Harwood Mattos, SVC (2007)


46. "Kathodenstaußbungenvorrichtung" ("Cathode sputtering device" with magnetic equipment which can be displaced to move the area of sputtering over an extended surface by relative movement), John F. Corbani, DE 2,707,144 A1 (Germany) (priority, Feb. 19, 1976; filed, Feb. 18, 1977; published Aug. 25, 1977) – moving magnet


About the Author

Donald M. Mattox

Don served as a meteorologist and Air Weather Officer in the USAF during and after the Korean War. After being discharged from the USAF he obtained an M.S. degree on the G.I. Bill, and went to work for Sandia National Laboratories in 1961. Don retired in 1989 after 28 years as a Member of the Technical Staff and then as a Technical Supervisor. Don was President of the American Vacuum Society (AVS) in 1983. In 1988, the 9th International Congress on Vacuum Metallurgy presented him with an award for “outstanding contributions to metallurgical coating technology for the period 1961-1988” and in 1995 he was the recipient of the AVS Albert Nenker Award for his work on the ion plating process. Don was the Technical Director of the Society of Vacuum Coaters (SVC) from 1989 to 2006. In 2007 Don received the Nathaniel Sugerman Award from the SVC. Don is presently the Technical Editor for the SVC.

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