Abstract
In October 1974, the first magnetron discharge supported by a pot magnet was carried out successfully at the former Manfred von Ardenne Research Institute (IvA). Similar developments were made in several countries in Europe and the US at that time. Inspired by this 40th anniversary, this article provides a brief survey of the history of magnetron sputtering and the driving factors behind the development of the sputtering technique into a reliable industrial process. Even if this development was also influenced by a major success in the US, the author focuses chiefly on developments in Europe. It also illustrates the progress of magnetron sputtering technology from small circular sputtering sources to industrially proven tools for large-area coating solutions.

How It All Began
Even though W.R. Grove observed the sputtering effect in 1852 as an undesired effect, there is no doubt that the father of magnetron sputtering was the Dutchman Frans Michael Penning, who had described a coating apparatus using a magnetic field support for cathode and anode in cylindrical arrangement as early as 1936 [1,2].

P.J. Clarke took up this idea in 1968. He combined it with means to reflect electrons towards the cylinder and improved the ionization ratio [3]. Seven years later he introduced the so called S-Gun design as shown in Figure 1, with a conic ring design of the cathode and abandoned the former cylindrical arrangement [4]. Nearly at the same time, J.S. Chapin proposed a planar cathode arrangement – and the term “Planar Magnetron” was born [5]. Both solutions already offered wider orifices for hitting more of the target surface with ions. However, they still suffered from low ionization rates so that the necessary deposition rates could still not be reached to push forward industrial application.

Another significant input was made in Russia, originating from a different application. In 1973, A.M. Dorodnov introduced a closed ring shaped magnetic arrangement for plasma accelerators for metallisation purposes at a conference in Kiev [6]. Dorodnov is also known as one of the developers of the mysterious ion engine that was used in the Russian space station MIR.

Independently from these developments, a small group of scientists and engineers at the former Manfred von Ardenne Research Institute (IvA) in Dresden, East Germany, which was headed by Ulrich Heisig, introduced a closed ring-shaped, inhomogeneous magnetic field nearby the cathode [7]. The setup was similar to the arrangement described by Dorodnov, and different from the homogeneous field of the mentioned classical arrangements. This magnetic field arrangement kept the electrons with a lateral drift along the path as long as they could provide energy for the ionization process. It caused the decisive increase of the ion current density on the target by a factor of up to 30, and influenced the deposition rate in a similar way. The first tests were made in 1974 in a very simple setup by use of a pot magnet originated from an ion getter pump, combined with an uncooled copper plate target. Last year, these initial tests were repeated with the original equipment to commemorate their importance (Figure 2).

The success of the initial tests facilitated a rapid development. In less than one year, the first planar magnetron PPS-5 was available for purchase at IvA. At that time, it was called Planar Plasmatron (Figure 3). Its performance of 5 kW discharge power by a 500 V discharge voltage and a sputter rate of 0.7 g/min for copper seemed to be very impressive in those days.
Everything Known In The 1980’s
The emerging development and progress in microelectronics that began in the 1970’s required efficient coating technologies, especially for the production of suitable resistors, transistors and rectifiers.

For the essential thin-film technologies, most of the evaporation techniques that had been used until then were limited with regards to the required film properties. As it was already known at that time, sputtering technologies offered a broad range of coating materials, but suffered from low coating rates. The breakthrough for magnetron sputtering coincided with increasing industrial demands that were mainly caused by the upcoming microelectronic industry.

Thanks to the ability to easily adapt the geometry of the closed ring due to the magnetic field, the planar target shape could be adapted to the required deposition arrangement. That was decisive for the technical development of high-rate sputter sources and explains the variety of sputter source types. Sputter sources in the power range from 1 kW to 100 kW and target dimensions ranging from a few centimeters up to some meters were applied (Figure 4).

The triangular magnetron is representative of the ability of the plasmatron discharge to adapt to the target shape. It is necessary for the homogeneous coating of substrates placed on planar rotary tables. The coating of large areas such as glass panes and polymer film called for the development of long-stretched high-power sources [7]. Already in the early 1980’s, large DC powered planar magnetrons were available at the IvA to answer that demand. They were 1.8 meters long, offered a power of 25 kW and were used in the first commercial inline architectural glass coating system, which was installed in East Germany (GDR) in 1983.

Figure 4. Different types of commercial available magnetron sputter sources, made by IvA in the mid 1980’s (Source: VON ARDENNE Corporate Archive)

Enforced by the rapid development of sputter sources and industrial demands, it did not take more than three years after the first initial tests to install the world’s first commercial horizontal sputter system HZM-4P with a rotary substrate holder (Figure 5). The IvA had achieved this in cooperation with the Centre of Research and Technology of Microelectronics (ZFTM).

Consequently, more than 100 of such inline coating systems were built in modular design, mostly for the microelectronic industry in East Germany behind the iron curtain. A few years later, similar sputter systems were manufactured in West Germany too. They were made by Leybold-Heraeus.

Figure 5. HZM-4 First commercial horizontal sputter system with a rotary substrate holder and equipped with PPS-5 planar magnetron, built 1977 by IvA (Source: VON ARDENNE Corporate Archive)

In the first years of high-rate sputter technology, most efforts were concentrated on the deposition of metals and alloys by DC powered sputtering for metallization purposes.

The industry also required non-conductive ceramic coatings, where high-rate sputter sources are suitable too. Furthermore, reactive sputtering came into focus, however at first limited to DC processes with need for conductive targets. Expenditures for high power RF generators and limited rates for layers from compound material still delayed the application. At the same time, in the early 1980’s, plasma emission monitoring was introduced to control the reactive process.

To overcome the limited efficiency, the idea of mid-frequency sputtering by use of two cathodes side by side was successfully implemented in the late 1980’s and became the standard in reactive sputtering processes for large-area coating applications for a long time.

The need for enhancing the target utilization in industrial applications led to several approaches such as moving targets and moving magnets until the rotatable magnetron became predominant. Finally, the 1980’s were a decade of a huge development in magnetron sputtering. Most of the basic principles that are still being used until this day were invented at that time, even if their industrial use often suffered from the lack of reliable technical solutions.

Rotatable Magnetron History Becomes a Global Story
Even if the big breakthrough of rotatable magnetron technology was in the late 1990’s, the principle had already been known since 1981. In that year, Mc. Kelvey, who worked for the small American glass coating Shutterproof Company, filed a patent that described a continued on page 24
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cylindrical target that was not yet rotating, but moved stepwise after the erosion groove in the racetrack reached the maximum [8]. Half a year later, another patent followed, filed by the IvA. It exclusively covered rotatable magnetrons with continuously rotating targets as we know them today [9,10] (Figure 6). Unfortunately, the huge potential of this principle was not recognized by the IvA at that time (6a) (Source: VON ARDENNE Corporate Archive)

Figure 6. First Rotatable sputter source RPS 25/500 with 500 mm target length, made by IvA in the mid 1980’s (6b). The magnet rotatable holder already was equipped with means for adjustment of the magnetic field (6a) (Source: VON ARDENNE Corporate Archive)

The idea of Mc. Kelvey was acquired by British Vacuum Technology (BVT), a Manchester-based company dealing with the coating of polymer web.

After the bankruptcy of Shatterproof in 1988, the patent portfolio came into the hands of Airco Solar, an Airco-Temescal company, located in Fairfield, California that belonged to the BOC group. Airco mainly worked on glass coating applications. Their goal was to exchange the planar Temescal cathodes with two rotatable ones.

The C-Mag set-up was born. In the mid 1990’s, Airco acquired BVT in an attempt to consolidate the rotatable magnetron expertise in a single company: Airco BVT. Even though Airco BVT sold equipment to several glass coating companies, Airco was not able to supply cylindrical targets of sufficient quality and quantity [11]. This gap has been identified at the beginning of the 1990’s by a small spin-off company of Ghent University, called Sinvaco. With the commitment of the driving people behind Sinvaco, H. Lievens, J. Vanderstraeten and R. De Gryse, the company was able to produce the cylindrical targets in the required quality. Although the target business became successful, the Airco rotatable magnetrons struggled with the harsh working conditions that are typical of glass coaters. In order to stay in business, Sinvaco was forced to solve these problems.

The Bekaert Company, which was already active in web coating and using BVT magnetron technology, showed some interest in the activities of Sinvaco. At the same time, Sinvaco and Airco became entangled in legal issues, a fact that facilitated the cooperation between Sinvaco and Bekaert. This resulted in the integration of Sinvaco into the Bekaert group after a few years of cooperation [11].

Airco BVT, which was later known as BOC Coating Technology, ran into difficulties and was acquired in 2002 by Von Ardenne Anlagentechnik, the successor of the former Manfred von Ardenne Research Institute. They completely redesigned the C-Mag type magnetrons and used them from then on for their inline glass coating systems and other products.

Thus the wheel had come full circle and the idea of Mc. Kelvey arrived at the company that had first invented and patented the original rotatable magnetron almost at the same time. This brief synopsis of rotatable magnetron history is also symptomatic of the described development, as both have overcome the borders between the US and Europe.

Reliable Industrial Technology as Result of Complex Influences

Nowadays, magnetron sputtering technology is well known as a reliable, robust and cost efficient industrial coating process and is widely used in many different branches. The number of magnetron sputter sources available on the market is very large, ranging from small planar magnetrons in different shapes and magnet configurations to large rotatable magnetrons of up to four meters in length.

When we look back, we have to take into account that this success story only was feasible as result of certain developments and innovations in different fields and in the further development of the magnetron source itself. These developments and innovations strongly influenced the performance of magnetron sputtering technology.

The major driving factors behind these improvements can be named as follows (Figure 7):

Figure 7. Major influences and drivers for magnetron technology, characterising the reliable industrial application

PROCESS STABILITY

Many sputtering applications are used in architectural glass and web coating. Many of them are in operation continuously for four weeks without interruption. Besides the target utilization, major developments have been made in power generators and power electronics, which have also been influenced by innovations in the field of renewable energies. These developments have led to a very stable and reliable operation of the generators.

The fast progress in microelectronics, digital technology and sensor development has made the plasma emission and optical control so fast and precise that it can be efficiently used for closed loop process control in reactive sputtering processes. This is done mainly to stabilize the process for a long time by increasing the sputter rates as much as possible.

Sputtering is always connected with particle generation. Many improvements of the design of the coater, the process guidance and the target quality can ensure long-term process stability. These improvements are influenced by display and barrier coating applications.
PERFORMANCE OF THE FILM
If you have to select what innovation had the greatest impact on the industrial dissemination of sputtering technology over the last 20 years, than progress in power supply performance, target material and manufacturing would probably be among the most important ones. The introduction of the DC pulse mode cleared the way for stable and efficient reactive sputtering of different compounds, slowly superseding mid-frequency power supplies. With bipolar pulse, a higher stability can be reached. A small positive potential is applied to the target between pulses. This can help to neutralize surface charges and reduce arcing [12]. All those developments were accompanied by very intelligent solutions in arc management and suppression, which were only feasible because of the huge developments in digital electronics and computing. The pulse mode and efficient arc suppression means were the key factors in stabilizing very sensitive processes, for instance those necessary for aluminum and silicon oxide coatings.

Mature thermal spray coating methods for tube targets and ceramic tiles for tubes with sophisticated heat conductivity improvements cleared the way for a wider range of materials to be applied with good economic sense. They were also a key factor for the strong growth of rotatable magnetron applications within the last two decades.

THICKNESS UNIFORMITY
Thickness uniformity itself is a result of several influencing factors and, especially in large-area coating, strongly determines, if magnetron sputtering technology is suitable or not. The fast development of turbomolecular pumps can be regarded as one major step, which superseded the former diffusion pumps very quickly in most applications. This, together with very sophisticated gas manifolds and fast responding flow controllers, allows for very sensitive adjustments of plasma parameters along the magnetron source. It should also not be forgotten that many improvements have been made in the magnetic configuration by using very strong and uniform magnets. As an example, thickness homogeneities of 0.4% could be proven for silicon nitride coatings on substrates of 3.3 meters width under production conditions in architectural coating.

COST OF OWNERSHIP
Nearly all the factors described above have a certain influence on the operating costs and have helped reduce these costs considerably over the last 20 years. In addition, real time control systems, the inline control of plasma parameters and smart automation systems may substantially help to reduce the manpower needed to operate such a coating machine which may have up to fifty magnetrons.

Finally, it can be stated that even if magnetron sputtering seems to be a very complex technology, it has benefited a great deal from the huge developments and innovations in all relevant fields connected with the sputtering process over the last 25 years. Today, magnetron sputtering is a reliable, highly developed and industrially proven technology, as it can be seen in the Figure 8 showing a rotatable magnetron of 3.7 meters length designed for architectural glass coating.

Summary
Magnetron sputtering took off about 40 years ago with astonishing speed. Within a very short period, magnetron sputtering sources were industrially used, after the first successful results had been achieved in significantly increasing the ionization rate. By the end of the 1980’s, the technology had been significantly further developed and most of the useful effects and technical principles with regard to sputtering cathodes and sputter processing were known. However, the technology still suffered from a lack of reliable, cost effective solutions and long-term stability.

The last 25 years could be characterized as the period when magnetron sputtering technology had been established in the industry, thanks to huge developments in power electronics, digital technology, vacuum components and materials. Today, this complex technology still suffers from a lack of reliable, cost effective solutions and long-term stability.

Figure 8. Actual design of high power rotatable dual magnetron RDM with 3750 mm target length (Source: VON ARDENNE Corporate Archive)
technology is relatively easy to apply. Apart from the US, several German pioneers on both sides of the iron curtain have fostered the development of magnetron sputtering. Notably the Manfred von Ardenne Research Institute and its successor Von Ardenne GmbH, Leybold-Heraeus and Balzers AG have been active in this field from the beginning. Furthermore, companies such as Bekaert, Hauzer, Gencoa, Oerlikon, but also several research institutes of the German Fraunhofer Society and universities in Uppsala, Chemnitz, Ghent, Aachen, Brunswick and Sheffield have advanced the development immensely.

It is thanks to those efforts that magnetron sputtering has become a technology with such a high level of perfection when it comes to large-area industrial applications at high rates and best layer properties with long-term stable and cost-efficient processing.

References

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