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High power pulsed magnetron sputtering: a game changer or an overrated technology?

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ABSTRACT

High Power Impulse Magnetron Sputtering (HiPIMS) is a method of Physical vapor deposition (PVD) that allows for the fabrication of high-quality thin films and provides improved control over the deposition process. HiPIMS accomplishes increased ionization levels within the target material by providing high peak power pulses at low duty cycles and frequencies to the sputtering target. This results in dense plasma and intense ion bombardment onto substrates. This produces coatings that are perfect for a variety of uses, including electronics, optics, and tool coatings, with the appropriate density, hardness, and surface defects. Although HiPIMS first appeared in the late 1960s, it gained popularity at the turn of the millennium and has since seen significant academic and commercial uses. HiPIMS has several drawbacks over traditional sputtering techniques, such as substrate restrictions, difficulties with process optimization, and greater setup costs; however, these are outweighed by its benefits over conventional sputtering methods in terms of film quality, productivity, and material properties, which make HiPIMS an invaluable tool for sophisticated thin-film deposition applications. HiPIMS has the potential to generate cutting-edge materials and satisfy the demands of upcoming industrial revolutions.

KEY WORDS

Plasma density, Substrate restrictions, Productivity, HiPIMS

ARTICLE HISTORY

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Introduction

High power impulse magnetron sputtering (HiPIMS) is a method of physical vapor deposition (PVD), where pulses at high peak power (up to 10 kW/cm2) are applied at the sputtering target at low duty cycle (up to 5%) and low frequency (hundreds of hertz) to allow cooling of the target. The effectiveness of the deposition process is improved by the presence of a magnetic field (magnetron) positioned behind the target, which serves to retain the plasma in proximity to the target.

The utilization of high peak energy leads to the formation of an exceedingly dense plasma and substantial ionization, reaching levels of up to 70% within the target material. This, in turn, permits an intensive bombardment of ions onto the coatings developing on the substrates biased with negative voltage. The coatings generated through this process typically exhibit the desired density, hardness, and are free from defects.

The initial concepts emerged in the late 1960s at the Moscow Engineering and Physics Institute (MEPhI), involving the application of high-power pulses to diode sputter sources. However, the utilization of high-power pulses on a magnetron target was introduced around the turn of the millennium [1,2]. To date, numerous scientific publications addressing HiPIMS have been released, which include not only research papers but also books [3] and review articles [4,5].

Owing to its notable ionization characteristics, HiPIMS exhibits potential as a replacement for arc evaporation, particularly in tool coatings. This potential arises from the similarities shared with target evaporation via cathodic arc discharge, which includes similar plasma density (on the order of 1018 m-3), comparable electron temperatures (ranging from 1 to 5 eV), and notably high ionization levels (up to 100%, with the possibility of multiple ionization). The significant amount of ions within the discharge permits fine-tuning of coating properties. This facilitates the production of exceptionally hard coatings for applications such as machining, milling, drilling, and various industrial uses.

Arc evaporation exhibits a notable limitation: it is linked to the release of large particles and droplets from the target surface, potentially resulting in coating defects. Although such defects may not necessarily compromise film functionality in numerous instances, situations demanding a flawlessly smooth film surface, particularly when specific tribological properties are essential, necessitate additional processes like polishing. In contrast, HiPIMS offers the benefit of generating defect-free coatings without the requirement for post-processing treatments. Despite almost a quarter-century passing since its initial reports, HiPIMS has not emerged as the primary method for magnetron sputtering. This can be attributed to its higher initial costs and relatively lower deposition rate. Standard direct current or pulsed direct current sputtering methods prove to be more cost-effective in terms of power supplies and provide superior deposition rates.

The reduction in deposition rate observed in HiPIMS results from a decrease in the effective sputtering yield, denoted as γeff (where γ represents the number of atoms sputtered by one incoming ion). When employing high-power pulses under the same magnetic field conditions, the

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discharge voltages tend to be higher in comparison to direct current sputtering. γ typically increases as the voltage is elevated. However, due to the presence of dense plasma and the influence of a strong magnetic field, a substantial fraction of the sputtered material becomes ionized, up to 70%. These ions are subsequently drawn back toward the negatively biased target. The effective sputtering yield is the number of atoms sputtered by one incoming ion that achieves the diffusion region (far from the target) and can be given by the following equation:

$$\gamma_{eff} = \gamma\,(1 - \alpha\beta)$$

where γ is sputtering yield, α is ionization probability (the probability that the sputtered atom will be ionized in the region close to the target), and β is back attraction probability (the probability that the sputtered ionized atom (ion) will be back attracted to the target surface).

HiPIMS technology has found its niche in various recent applications, prompting some companies to specialize in its use. These companies offer comprehensive coating solutions, including deposition devices and coating recipes (e.g., CemeCon, Hauzer), as well as power supplies (e.g., Nano4Energy, Starfire, and Ionautics). HiPIMS technology is particularly advantageous in the field of micro-tool coatings. Herein, post-process polishing may not be favorable or even feasible. The high batch size, enabled by the small size of these tools, keeps the cost per tool reasonable despite the lower deposition rate and the elevated cost of the HiPIMS process. Another notable application is in decorative coatings. Here, ions can be selectively attracted to substrates, ensuring the homogeneous coloring of the substrates with minimal interference colors. In recent years, a wide array of colors with exceptional mechanical properties have become available in the market. This is especially relevant to the coating of displays and covers for mobile phones or smartwatches, where there is a high market demand.

With its many benefits, High Power Pulsed Magnetron Sputtering revolutionizes thin-film deposition. It produces films with improved adhesion, density, and uniformity, making them ideal for a variety of uses in the electronics, optics, and automotive industries. This method provides precise control over the composition of the film, making it easier to deposit complex materials and multilayer structures with customized characteristics. Additionally, HIPIMS maximizes productivity by achieving greater deposition rates and avoiding substrate heating, hence broadening its use to temperature-sensitive materials. Especially, it provides precise control over texture and residual stress, which is essential for maximizing mechanical and optical qualities. HIPIMS is versatile enough to work with a wide range of materials and substrates, and its scalable solutions guarantee consistent quality in a wide range of applications. It also lowers operational costs and extends target lifetimes by consuming less target material.

While High Power Pulsed Magnetron Sputtering has many benefits, it also has certain disadvantages. First off, because more specialist equipment and knowledge are needed for its setup and upkeep than for traditional DC sputtering systems, they are more complex and expensive. Second, even with measures to reduce substrate heating—especially with regard to temperature-sensitive materials—HIPIMS may still have an adverse effect on substrate compatibility. Furthermore, it can be difficult to optimize process parameters for HIPIMS, requiring a great deal of effort to precisely adjust deposition conditions for the required film qualities. Because HIPIMS is pulsed, it presents additional difficulties, such as pulse-related impacts on film microstructure and stress, which call for careful thought and mitigating measures. Furthermore, while HIPIMS lessens target degradation in comparison to DC sputtering, it still necessitates routine replacement and maintenance, which affects process uniformity and stability.

One prominent thin-film deposition method that offers several benefits to a variety of industries is HIPIMS. Applications such as optical coatings, where HIPIMS enables the fabrication of high-performance anti-reflective coatings for lenses, serve as prime examples of their capacity to generate outstanding film quality. Furthermore, because HIPIMS has higher deposition rates, which result in quicker production cycles and lower manufacturing costs, it increases productivity, especially in the electronics manufacturing industry. As demonstrated in the semiconductor industry, where HIPIMS is used to deposit thin films with precise mechanical, electrical, or magnetic characteristics for microelectronic devices, this technology also makes it easier to deposit sophisticated materials with tailored properties. Furthermore, HIPIMS-deposited coatings offer improved wear resistance, which is advantageous for uses where durability is crucial, such as cutting tools and automotive components. HIPIMS systems provide long-term energy efficiency benefits by limiting substrate heating and target erosion, which eventually results in lower power consumption and material utilization despite their initial complexity and cost. These illustrations highlight the ways in which HIPIMS's benefits—such as its higher film quality, increased productivity, sophisticated material deposition capabilities, and energy efficiency—make it the system of choice for a wide range of industrial applications, spurring innovation and performance in a number of different industries.

Indeed, HiPIMS technology offers distinct advantages, primarily for researchers, granting them greater control over the deposition process and facilitating the exploration of new frontiers in PVD-coated materials. Among the many benefits of High Power Pulsed Magnetron Sputtering are improved production, better control over film properties, and higher film quality. From an industrial perspective, the benefits of HiPIMS in comparison to direct current sputtering or arc evaporation are relatively modest, often outweighed by several drawbacks. As of now, only specialized and emerging markets express a significant interest in this technology. Although HIPIMS has certain limitations, including substrate restrictions, difficulties with process optimization, and complexity in setup and maintenance, these are generally outweighed by the technique's advantages, which makes HIPIMS a useful tool for sophisticated thin-film deposition applications. However, as we consider the ongoing industrial transformation, the growing utilization of renewable energy sources, and the development of the hydrogen economy, there arises a pressing demand for exceptional materials. In this context, HiPIMS may hold the potential to enable the creation of materials that meet the demands of the future.

Disclosure statement

No potential conflict of interest was reported by the author.

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