Substrate Biasing for Sputter Deposition Processes

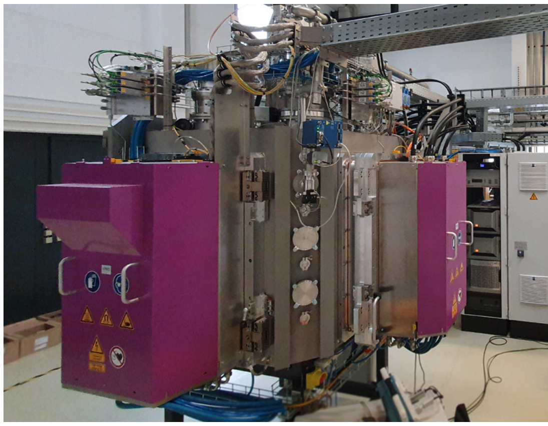
Exploring advanced coating techniques and solutions for precise film quality

Introduction

Substrate biasing in sputter deposition processes is a critical technique for enhancing thin-film properties. This paper explores the principles and practices of substrate biasing, examining its impact on thin-film characteristics and the various methods used to achieve optimal results. It also discusses advanced biasing techniques and their applications, providing a comprehensive overview of the technology and its benefits in thin-film deposition.

By integrating substrate biasing into deposition systems, greater control over film properties can be achieved, enabling the development of coatings with enhanced performance characteristics. Through this in-depth analysis, we aim to guide readers through the complexities of substrate biasing and offer valuable insights into its practical implementation with modern solutions from Advanced Energy.

Table of Contents



Advanced Energy's industrial drum coater.

UNDERSTANDING PLASMA POTENTIALS IN MAGNETRON SPUTTERING

Sputtering utilizes a glow discharge between a negatively (-) charged cathode and a positively (+) charged anode. The discharge between the cathode and anode is maintained by an applied voltage, typically in the order of several hundred volts. Contrary to a simple ohmic conductor, like a wire or resistor, the electric potential between the (+) and (-) poles is non-linear in location.

A linear glow discharge can be divided into three distinct zones: (i) the cathode zone, containing most of the potential rise, (ii) the plasma bulk, characterized by a small and relatively constant potential rise, and (iii) the anode zone, which exhibits a sharp but comparatively small change in potential [1]. In more complex geometries, like a dual rotating cathode magnetron sputtering chamber, the electric potential exhibits a more complex layout. As an example, Figure 1 shows the simulated electric potential in Advanced Energy's drumcoater during simultaneous sputtering from both cathodes against the single shared anode [2].

The main process in sputtering involves the ejection of atoms from the cathode material (the target) by using the momentum of relatively heavy inert gas ions like argon. A magnetic field at the target material leads to a high concentration of these ions near the target. The argon ions gain momentum by the large potential rise in the cathode zone to then hit and erode the target material. While the target material is ejected mostly as neutral atoms, unable

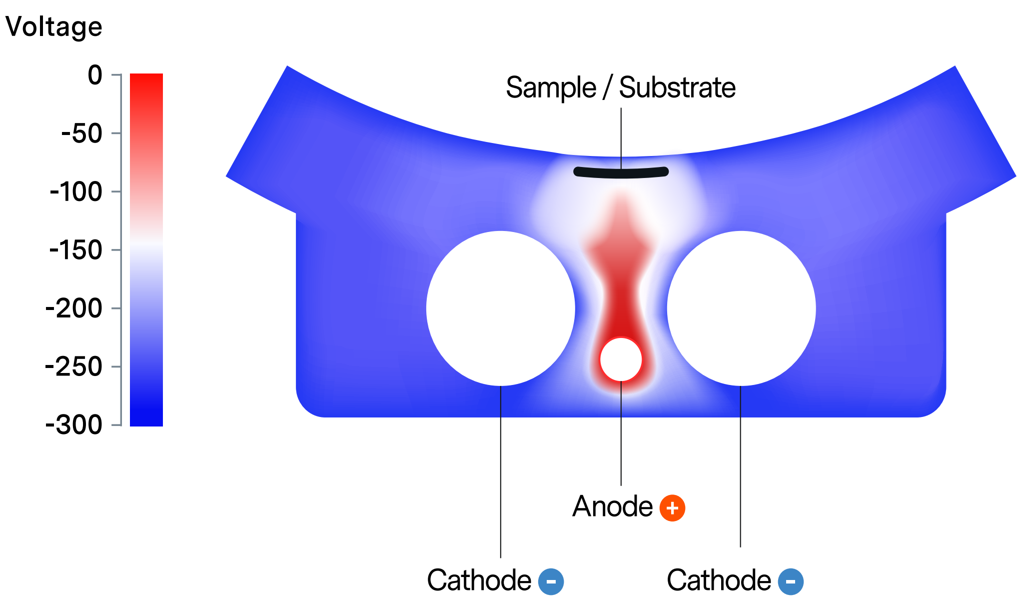


Figure 1: Cross-sectional view of a simulated plasma potential during sputtering with two targets and a shared anode.

to be affected by any electric potential, a small but considerable amount of ionized target material exists in the plasma.

Since the substrate is typically positioned within or near the plasma bulk, both sputtered material from the cathode and charged plasma species can reach the substrate. Their transport is influenced by sputtering conditions and potential gradients, depending on their respective charges. These conditions dictate the coating structure and thereby the coating properties.

With such a setup, it is apparent that controlling the energy of the species arriving at the substrate would affect the coating growth. This can be done by applying a substrate bias by utilizing a dedicated bias power supply at the substrate. The bias, usually negative as compared to the plasma bulk potential, influences the acceleration of the plasma ions to the substrate. The energy of these ions can be adjusted by the type of substrate bias applied, allowing them to directly affect the film's growth and, in turn, help fine-tune the coating properties. Hence, substrate biasing provides an independent mechanism to control the coating growth on the substrate and help achieve desired properties according to the application needs. The actual change brought about in the coating by applying substrate biasing can be diverse, affecting structure and functional properites.

One application where substrate biasing is frequently used is in the field of hard coatings. Hard coatings are extremely thin protective films that improve the surface properties of a material, including increased hardness, strength, oxidation resistance, and tunable adjustments to friction. These improvements are achieved compared to a coating applied without any additional substrate bias.

MANIPULATING ION ENERGY FOR ENHANCED FILM PROPERTIES

In magnetron sputtering chambers, substrate biasing helps control the coating’s properties by using ionized target material and ionized sputtering or reactive gases in the plasma. This can improve adhesion or change the surface structure of the coating [3].

The idea of using substrate bias is to extract ions from the plasma bulk and alter their energy at the substrate. This is achieved by providing a separate – different from the cathode – negative electric potential at the substrate surface, which can thus attract positively charged ions. The magnitude of this potential has an influence on the ion energies impinging on the substrate surface.

DELIVERING POWER TO THE SUBSTRATE

Various methods are available for delivering power to the target to ensure effective sputtering. Additionally, a range of power supply configurations can be employed to tune the substrate bias potentials for effective ion impingement.

Deposition tool setup with sputtering and bias power supplies

Figures 2 and 3 show generic sputtering thin film deposition chambers. Besides the vacuum system (pumps, pipes, and valves) and the gas delivery system (sputtering gases, and mass flow controllers) not shown, they consist of the sputtering target, powered by a dedicated source power supply (either a DC, pulsed DC, or RF power supply) and the substrate holder, which can also be connected to a power supply that provides bias.

The following sections show different types of bias power supplies.

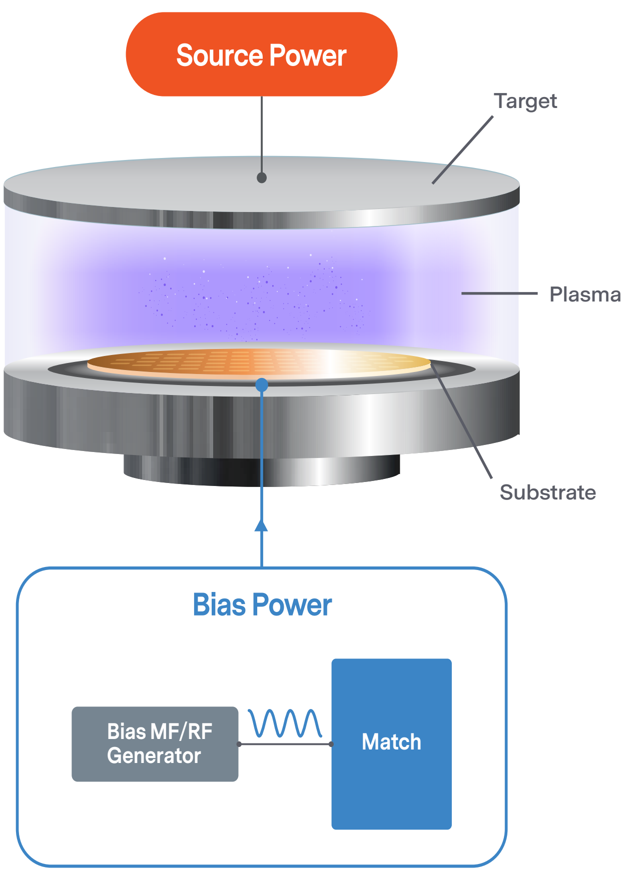


Figure 2: Deposition tool overview with sputtering and MF or RF generator combined with a matching network for bias power.

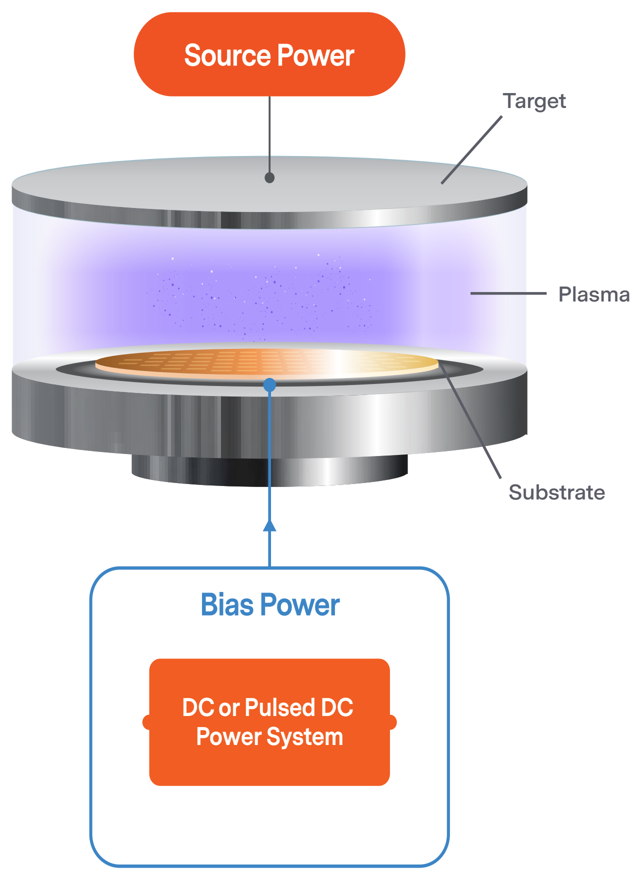


Figure 3: Deposition tool overview with sputtering and DC or pulsed DC system for bias power.

DC Without Pulsing

A power supply is connected to the substrate holder. Its output is controlled to hold a set voltage between the substrate holder and the chamber. The current to sustain this voltage is constant and related to the number of ions arriving at the substrate holder. Since an arc occurring at the substrate could persist indefinitely without pulsing, effective arc suppression and management are critical.

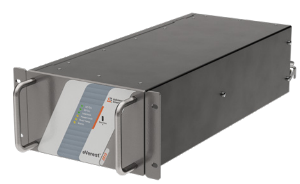
For DC solutions without pulsing, Advanced Energy offers the Pinnacle®, Solvix®, and Ascent® power supplies.

Pulsed DC

To maintain an arc-free deposition process, the substrate bias is periodically pulsed—typically in the kHz range—to allow for substrate discharge and prevent charge accumulation. It also helps to prevent the buildup of local charges on the substrate surface, especially for non-conductive films. These charge build-ups otherwise counteract the effect of the biasing potential. Moreover, the biasing frequency can be used as an additional parameter for tuning the coating properties.

Pulsed DC solutions offered by Advanced Energy for biasing applications are the Pinnacle Plus, Solvix, and Ascent power supplies.

Radiofrequency (RF) and Mid-Frequency (MF) Sinusoidal Voltage



RF (in the range of several MHz) and MF (usually 400 kHz) sinusoidal voltages can also be applied to tune the substrate bias potential. Here, large voltages are applied, alternating rapidly. In this regime, the mass difference between ions—which are too heavy to react within a single voltage period—and electrons in the plasma leads to an average negative potential at the substrate. For this reason, RF biasing can also be effective for non-conductive films. However, the requirements for an additional matching network as well as special coupling to the substrate holder should be kept in mind.

For RF and MF substrate biasing applications, Advanced Energy offers the Paramount® MF, Paramount, and eVerest® generators for use together with the Navigator® II and NavX™ matching networks.

Asymmetric Bias Waveforms

An asymmetric waveform allows tailoring the energy distribution of the ions bombarding the substrate [4]. The advantage of selecting a narrow ion energy distribution has proven highly beneficial for etching applications in semiconductor processes. The ability of this bias supply to selectively impact the ion energy distribution provides an interesting tool for etching applications and for influencing the plasma species during film deposition.

Advanced Energy offers the eVoS® bias solution for semiconductor applications.

INFLUENCE OF PROCESS VARIABLES ON SUBSTRATE BIASING OUTCOMES

Besides applying the right potential to the substrate surface, there are other aspects in the thin film tool and process to consider when introducing an additional bias. We look at some factors influencing the effectiveness of substrate biasing on altering coating properties.

Sputtering power delivery

The sputtering technique itself has a large influence on the number of ions in the plasma. DC sputtering offers only a few ionized species, however, pulsed-DC sputtering leads to the creation of some ionized species at the start and end of each sputtering pulse [5]. High-power impulse magnetron sputtering (HiPIMS) offers higher ionization due to its large voltage and peak current during each sputtering pulse [6].

A larger ionization in the plasma leads to an increased potential for tuning the properties of the coating when applying a bias potential to the substrate.

Location of the substrate

As discussed earlier, substrates are typically not placed directly between cathode and anode, but rather outside of this direct current path. Although the plasma bulk extends into the vacuum chamber, its density, and thus the ion density, decreases with distance. The closer a substrate is to the sputtering plasma, the larger the effect of substrate bias is expected to be.

Resistivity of the coating

The electric potential at the substrate surface can only be directly controlled if the coating is conductive and electrically connected to the substrate holder, where the bias power supply is applied. However, if the substrate surface is non-conductive, the power supply can only apply the desired voltage to the layer below while the insulating top coating acts as a capacitor.

When a DC bias is applied to non-conductive substrates, positive ions are initially attracted to the substrate surface. This continues only until the electric field is neutralized. After that point, charges begin to accumulate on the surface, which prevents further attraction of ions from the plasma bulk.

For substrates with nanostructures, this surface charging can create extremely high local electric fields within the substrate, potentially causing damage.

Pulsed-DC biasing regularly discharges the substrate and thus increases the effectiveness to extract ions from the plasma onto non-conductive substrates.

RF biasing offers an alternative for non-conductive substrates. Here, the electric potential of the substrate holder is rapidly alternating between positive and negative charging. This polarity change in the MHz range is too fast for the heavier ions to follow in each period due to their mass, while the lighter electrons can follow. Averaged over many cycles, this results in an effective negative potential at the substrate, regardless of conductivity, yielding a small attraction for the plasma ions.

A tabular overview of the relationship between the conductivities of substrates and suitable biasing techniques can be found in Figure 4.

		DC	Pulsed-DC	RF / MF
Conductive Substrate	+ conductive coating	✓✓	✓✓	✓✓
	+ insulating coating	x	✓✓	✓✓
Insulating Substrate	+ conductive coating	✓	✓✓	✓✓
	+ insulating coating	x	x	✓

Figure 4: Compatibility matrix of substrate bias power supplies with coating processes.

x : This supply type is unsuitable for biasing this material system.
✓ : This supply type can be used with limitations.
✓✓ : This power supply type is generally well suited.

Substrate mounting

There are a wide variety of sputtering tool types. While it is relatively straightforward to apply a bias to substrates that are fixed in the chamber, it becomes more challenging to control the electric potential when the substrates are moving. Another factor is coating a substrate without any shadowing. This would make it impossible to use clamps to provide an electrical connection between holder and substrate surface, limiting its use to only conductive substrates.

Substrate bias voltage

The main parameter, when controlling biasing is the voltage of the substrate surface with respect to the plasma bulk. As discussed, a larger voltage will increase the energy of the impinging ions on the film surface. This momentum transfer and surface diffusion allows for enhanced atom mobility, leading to densification of the film. Due to the higher density and the ion impingement removing loosely bound atoms from the growing film, it usually appears as a reduction in thickness, i.e., the deposition rate decreases slightly for small bias voltages, as shown in Figure 5.

When higher bias voltages are applied, ions can gain enough momentum to penetrate deeper into the film, which may cause defects. As the voltage increases to several hundred volts, the ions' momentum becomes sufficient to sputter atoms from the substrate surface, similar to ion beam etching. At this point, the deposition rate can even turn negative. This high-bias regime can be intentionally used to clean the sample surface, with the sputtering source serving mainly as a donor of ionized species and typically operating at much lower power.

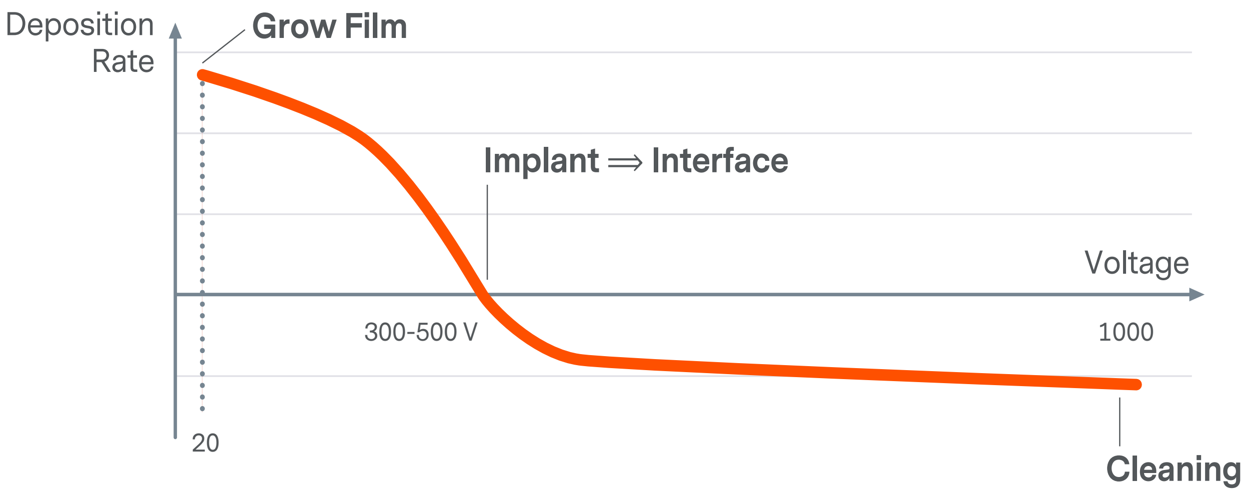


Figure 5: General graph showing the influence of biasing voltage on the deposition rate of a sputtering process. High bias voltage leads to an effective abrasion of the substrate surface and thus a negative deposition rate.

CONCLUSION

This whitepaper discussed several aspects of substrate biasing for sputtering applications, highlighting how the integration of a bias power supply into the deposition system can increase the parameter space and allow for separate control of the ion energies arriving at the substrate surface.

With thoughtful planning and the right setup, substrate biasing can deliver substantial advantages in sputter deposition processes. While the technique introduces additional complexity, its benefits are particularly evident in the production of coatings with enhanced hardness and density, making it especially valuable for applications such as cutting tools and scratch-resistant decorative finishes.

To determine whether biasing is the right fit for your specific needs, we encourage you to connect with your local AE sales representative and talk to our experts who can tailor a solution that aligns with your performance goals and operational requirements.

We have a broad portfolio of reliable power delivery solutions that are ideal for industrial coating manufacturers.

REFERENCES

[1] A. Anders, Appl. Phys. Rev. 11, 031310 (2024).

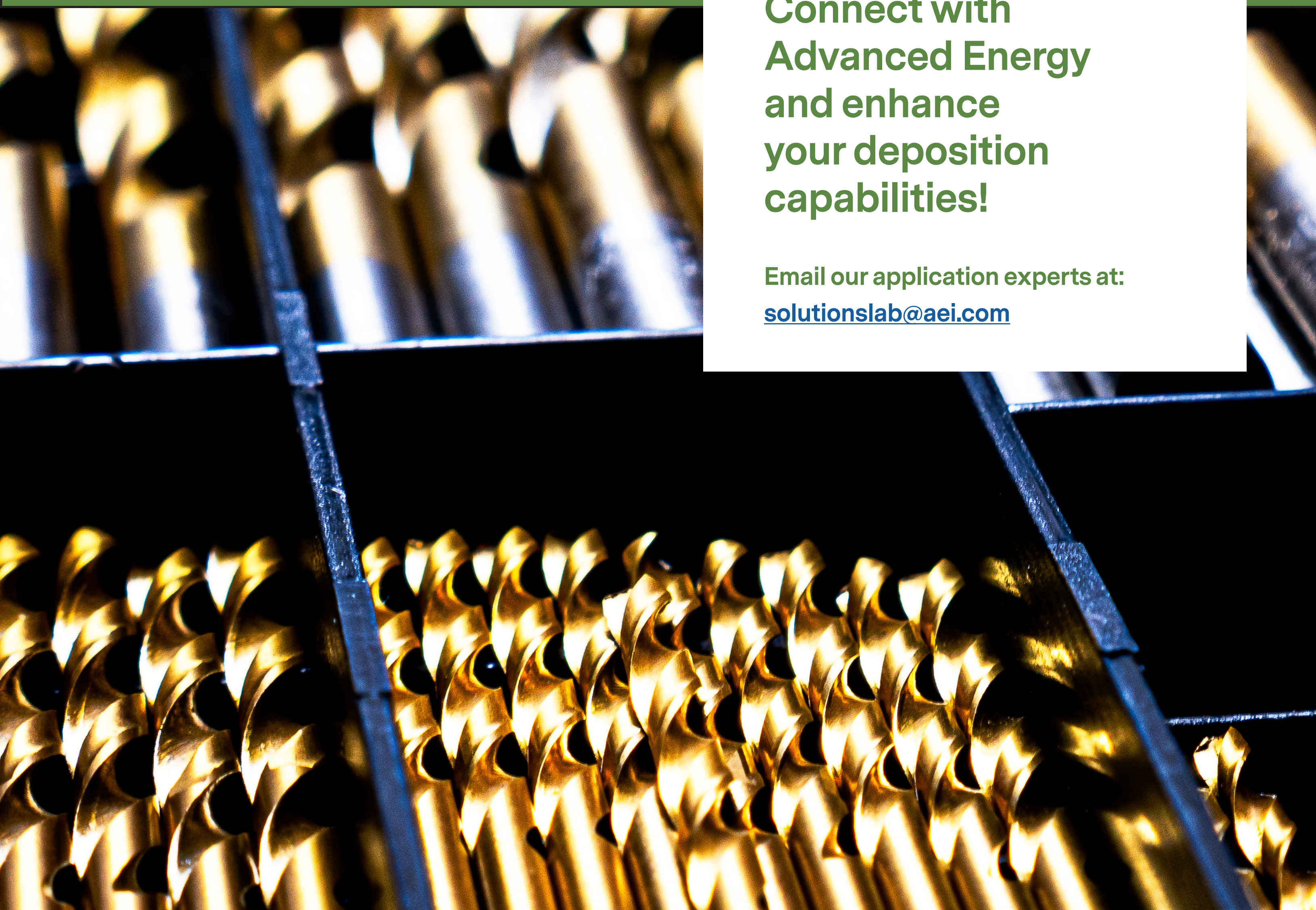
[2] G. Rane, A. Obrusník, M. Kubečka, K. Tomanková, P. Dürrenfeld, U. Krause, D. Shaw, Surf. Coat. Technol. 502, 131975 (2025).

[3] P. J. Kelly, R. Hall, J. O'Brien, J. W. Bradley, G. Roche, R. D. Arnell, Surf. Coat. Technol. 142–144, 635 (2001).

[4] Y. Y. Samoilenko, T. G. Jenkins, D. M. Shaw, "Asymmetric Power Biasing for Critical Plasma Semiconductor Processes," Semicond. Dig. Magazine, 17 (June 2025).

[5] M. Misina, J. W. Bradley, H. Bäcker, Y. Aranda-Gonzalvo, S. K. Karkari, D. Forder, Vacuum 68, 171 (2003).

[6] U. Helmersson, M. Lattemann, J. Bohlmark, A. P. Ehiasarian, J. T. Gudmundsson, Thin Solid Films 513, 1 (2006).



ABOUT ADVANCED ENERGY

Advanced Energy (AE) has devoted more than four decades to perfecting power for its global customers. We design and manufacture highly engineered, precision power conversion, measurement and control solutions for mission-critical applications and processes.

Our products enable customer innovation in complex applications for a wide range of industries including semiconductor equipment, industrial, manufacturing, telecommunications, data center computing, and medical. With deep applications know-how and responsive service and support across the globe, we build collaborative partnerships to meet rapid technological developments, propel growth for our customers, and innovate the future of power.

PRECISION | POWER | PERFORMANCE | TRUST

For international contact information,
visit advancedenergy.com

powersales@aei.com
techsupport@aei.com
+1 866.865.5180

ENG-Substrate-Biasing-Sputter-Deposition-Processes-275-01 12.25