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High Performance Power Supplies for Plasma Materials Processing

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ABSTRACT Integrated circuits, flat panel displays, solar panels, architectural glass, high resolution camera and many other products are landmarks of the 21^{st} century. All of these different everyday objects have one thing in common - they are manufactured using plasma processing techniques. The aim of this paper is to introduce this silent hero of modern industry, to a broader audience. An evaluation is made of common types of power converters within the scope of plasma processing applications, while the key requirements and future challenges for such power supplies are discussed.

INDEX TERMS Plasma applications, plasma materials processing, power conversion, power electronics.

I. INTRODUCTION

Plasma processing techniques are routinely used in the manufacturing of various types of commonly used equipment – from corrective lenses to drills, surgical equipment and architectural glass to the integrated circuits used in smartphones, laptops, and cars. In other words, the modern world would hardly be recognizable without plasma processing techniques. This broad scope of applications is mainly covered by two types of plasma processes: Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD), in both of which the plasma has to be excited and sustained by a dedicated high-performance power supply. The wide variety of manufacturing processes where plasma is used has triggered the development of a large family of plasma power supplies, from devices using straight DC or pulsed DC up to the radio- (RF) and ultrahigh-frequency (VHF) ranges, with power ratings of from several hundred watts up to hundreds of kilowatts.

The goal of this paper is to introduce the application of power converters in plasma processing to a broader audience. Examples of plasma processing applications provide a background for discussing the unique and rigorous requirements for high-performance power electronic converters used in plasma systems – from current shaping to reliability. In section II, the foundations of plasma processing techniques are presented, while section III discusses typical applications of plasma processing techniques and their influence on the main functional requirements for power supplies. Finally, section IV takes a look at future trends and challenges for power supplies used in state-of-the-art plasma systems.

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II. PLASMA PROCESSING TECHNIQUES

The plasma processing technique is used to change the properties of the surface exposed to the plasma. This may involve covering a bare surface of, e.g., a metal with single or multiple thin layers of another material. The modification of a surface with a thin coating, called also *deposition*, is used in the manufacture of many of the industrial products we encounter every day. In the case of metal elements, such as drills, the coating can consist of titanium nitride (TiN), chromium nitride (CrN), or a mixture thereof [1]. Bio-compatible protective layers for joint implants in medical applications are manufactured in a similar process [2], whereas another example is thin optical coatings, which nowadays are an inherent part of the glass industry. Windows and glass facades are made of what is known as Low-E glass, where a thin multi-layer coating helps to control the heat transfer between the outside and inside of a building while providing satisfactory transparency for visible light [3].

Similar examples of widely used coatings are UV shields (e.g. for glasses) [4], anti-reflective coatings on glass surfaces (e.g. for architectural glass) [5] or reflective surface manufacturing (e.g. for industrial mirrors) [6]. Plasma-deposited decorative coatings are routinely applied on a variety of products such as bathroom taps, mobile phones and eyeglasses [7]–[9].

Plasma can also be used for the removal of a defined thickness of a surface or for the precise, selective removal of certain parts of a substrate. By means of non-selective surface removal one can obtain a defect- and contaminant-free surface (called also *dry cleaning* or *plasma cleaning*), to ensure good adhesion between the substrate surface and the coating deposited in the next steps of the process. In contrast, selective removal is known as *plasma dry etching process*, and is used, e.g., in the manufacturing of semiconductors. Conventional chemical etching, cleaning and solvent degreasing tend to leave pits or residual traces of process chemicals on the treated surface, whereas plasma-based cleaning and etching processes eliminate this drawback.

Although much of the industrial surface processing by plasma is performed in high- or ultrahigh-vacuum conditions as a consequence of the quality requirements for the final coating or surface properties, there are many plasma processes performed at pressures close to atmospheric levels, referred as Atmospheric Pressure Plasma (APP). These types may be used for the generation of free radicals (e.g. O_3) [10], the emission of ultraviolet (UV) or vacuum-ultraviolet (VUV) photons (e.g. for microbial disinfection [11]), the decomposition of hazardous or toxic compounds (e.g. NO_X, SO_2) or surface activation, to name just a few applications [12], [13]. The main advantage of APP over PVD methods is that it takes place at ambient pressure, which makes it possible to eliminate the high cost of a vacuum chamber and its associated components.

In the next section, we present a short description of each type of plasma process routinely used in industry.

A. CHEMICAL VAPOR DEPOSITION

Chemical Vapor Deposition is a group of deposition methods where a coating is formed from chemical constituents reacting in the vapor phase near or on a heated surface. The basic form of CVD is thermal chemical vapor deposition, also called vapor plating, where a precursor species containing the material to be deposited is vaporized by the application of a high-temperature source. The vaporized precursor species reacts with other gaseous species present inside a vacuum system to form compounds (e.g. oxides, nitrides). Depending on the technical aspects of the process, various modifications of CVD methods are available, such as: vapor phase epitaxy (VPE), used for single crystal film deposition [14]; Plasma-Enhanced CVD (PECVD) or Plasma-Assisted CVD (PACVD), where plasma is used to induce or accelerate the decomposition or reaction factor of a material [15], low-pressure CVD (LPCVD) [16], for processes that do not require vacuum conditions as high as those in VPE; and metal-organic CVD (MOCVD), where the precursor gas is a metal-organic compound [17]. The main advantage of Plasma Assisted- or Plasma-Enhanced Chemical Vapor Deposition (PACVD/PECVD) over thermal CVD is the possibility it affords of reducing the activation temperature of the chemical reactions from above $700°C$, down to $300 - 500°C$.

Although CVD and PECVD are mostly used for film deposition (e.g. in LCD manufacturing [18]), they can also be used for the removal of a coating from a surface in the dry etching process. The plasma sources used for chemical etching are similar to those used for plasma-enhanced chemical vapor deposition. Precursor gases for chemical etching are selected such as will chemically react with the layer to be etched. An excellent example is nitrogen trifluoride (NF_3) which, after decomposition in plasma, releases highly reactive fluorine radicals and ionized fluorine compounds that react with Si or SiO_2, thus removing it from the wafer. The resulting compounds are removed from the process chamber by a pumping system and, due to their toxicity, are then decomposed to environmentally safe products in a plasma-assisted *gas abatement* process [19].

Furthermore, physical and chemical etching processes can also be combined in the form of a *Reactive Ion Etching* (RIE) process – of key importance in the manufacturing of semiconductors [20]. This method combines ion bombardment of a negatively biased substrate (Si wafer)) – which leads to the removal of the silicon – with the chemical etching of the film. Such a process therefore requires at least two power supplies: one for the plasma source where the ions and reactive radicals are formed, and another to negatively polarize (bias) the substrate to attract and accelerate ions to the surface being etched away. Because this technique makes it possible to etch structures of a very high aspect ratio (HAR), it is widely used in the semiconductor industry: from Through-Silicon Vias (TSV) manufacturing [21], through nanocarbon film etching [22], to GaN and Si surface treatment [23], [24].

A schematic view of a PECVD vacuum system is presented in Fig. 1. In particular, this is an ICP (Inductively Coupled Plasma) system geometry where the plasma is generated by a coil surrounding the cylindrical dielectric wall of the source region. Process gases are injected into the chamber through the source region and the plasma expands from there into the processing chamber, where the substrate is located. The ICP coil is supplied by an RF generator (i.e. 13.56 MHz), while the substrate, the material whose surface properties are to be modified, is placed on the substrate holder equipped with heaters, wafer cooling, sensors (e.g. temperature), and reference markers for the substrate positioning system. Further, the substrate holder permits the application of a bias voltage to the substrate using an RF power supply with the same or a lower frequency than that of the plasma source. Depending on the design, the substrate holder can be also connected to an additional DC power supply to apply high-voltage pulses in order to generate an electrostatic potential on the substrate holder surface for wafer positioning.

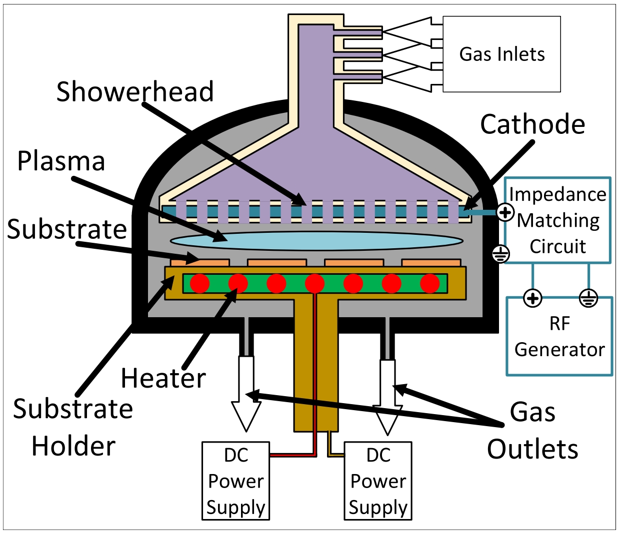


FIGURE 1. **Simplified cross section of typical plasma chamber for a plasma-enhanced chemical vapor deposition process.**

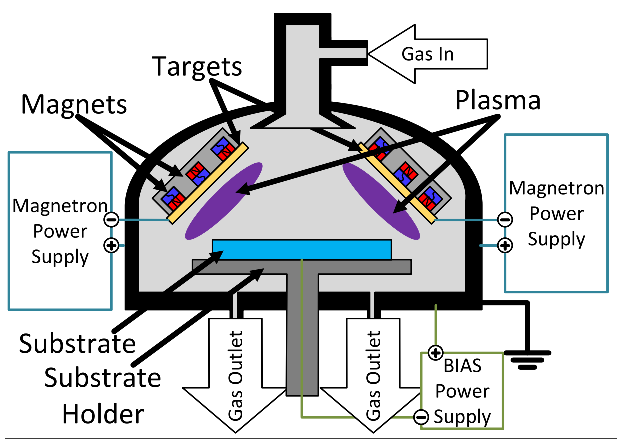


FIGURE 2. **Simplified cross section of plasma chamber for a plasma vapor deposition process.**

B. PHYSICAL VAPOR DEPOSITION

PVD is an extensive group of deposition processes in which a source material (called also a target) is vaporized and the vapor is then settled on a substrate to form a coating. Depending on the desired properties and composition of the deposited film, the process may require the use of single or multiple targets, each of which may consist of one or more elements.

PVD techniques can be distinguished by how the source material vapors are produced. In evaporation, the target is heated up to its melting point to release particles of the source material into the processing chamber [25]. Alternatively, the target material may be vaporized using a beam of high-energy electrons or ions [26]. In the case of magnetron sputtering, the target is eroded by bombardment with energetic ions. In both evaporation and sputtering, the next step is similar – the released target particles settle on the substrate. Additionally, if the target particles are ionized, a high electric potential may be applied to the substrate in order to accelerate the incoming ions and increase the density of the growing film. This procedure is called *substrate biasing*, and is further discussed in section III.

The main advantage of sputtering over evaporation is the higher energy of the released target particles, used to increase the density of the coating and thereby improve its properties. Each PVD method sets different requirements for the power converters used in the plasma process. As in the evaporation process, a simple DC current source can be applied, for magnetron sputtering a variety of power supplies are used routinely in the industry due to the complexity of various applications.

In physical dry etching or plasma cleaning, as mentioned above, the kinetic energy of the accelerated ions is used to remove layers from the surface. Typically, such a process uses argon as the working gas. Argon ions available in the plasma are accelerated in a high electrical field introduced by the bias power supply. The proper adjustment of the negative voltage amplitude and process gas composition allows precise control over the thickness of the layer removed.

A model of a typical process chamber used for magnetron sputtering is shown schematically in Fig. 2, while a detailed description of the magnetron sputtering process can be found in monograph [27]. Here only a basic description will be given of the working environment of a power converter used for plasma processing. To ensure the required processing conditions and avoid impurities, plasma processes are usually performed in a vacuum or a low-pressure environment. For example, in the case of magnetron sputtering, after the air is pumped out, the process chamber is filled with an inert gas such as argon. The power converter, e.g. a Pulsed DC power supply, is connected to the target (cathode) and to the chamber walls (anode) to provide the necessary energy to ignite and sustain the plasma discharge. Behind the target, a magnetron is placed to "trap" electrons in the vicinity of the target and increase the ionization of the inert gas in this area. The ionization process initially requires electrons. The electric field generated by the power supply accelerates the electrons towards the anode, and gas ions towards the cathode. Collisions of atoms with each other and with the electrons initiate a snowball process of ionization. When ions hit the target surface, their kinetic energy is transferred to atoms on the surface. If that energy is sufficient, the atomic bonds are broken and the target atoms are ejected from the surface. Due to collisions, secondary electrons are also emitted from the target. Before reaching the surface on which the film is grown, the target atoms can be ionized or excited by collisions with plasma particles.

In many cases, a magnetron sputtering process involves using a second power supply connected to the substrate on which the film is deposited. Depending on whether the substrate is electrically conductive or not, a DC, Pulsed DC, or RF power supply is used as the bias source. The application of a negative potential (with respect to the grounded chamber wall) provides additional kinetic energy to the ionized target material. This excess energy is beneficial to the density and morphology of the deposited film.

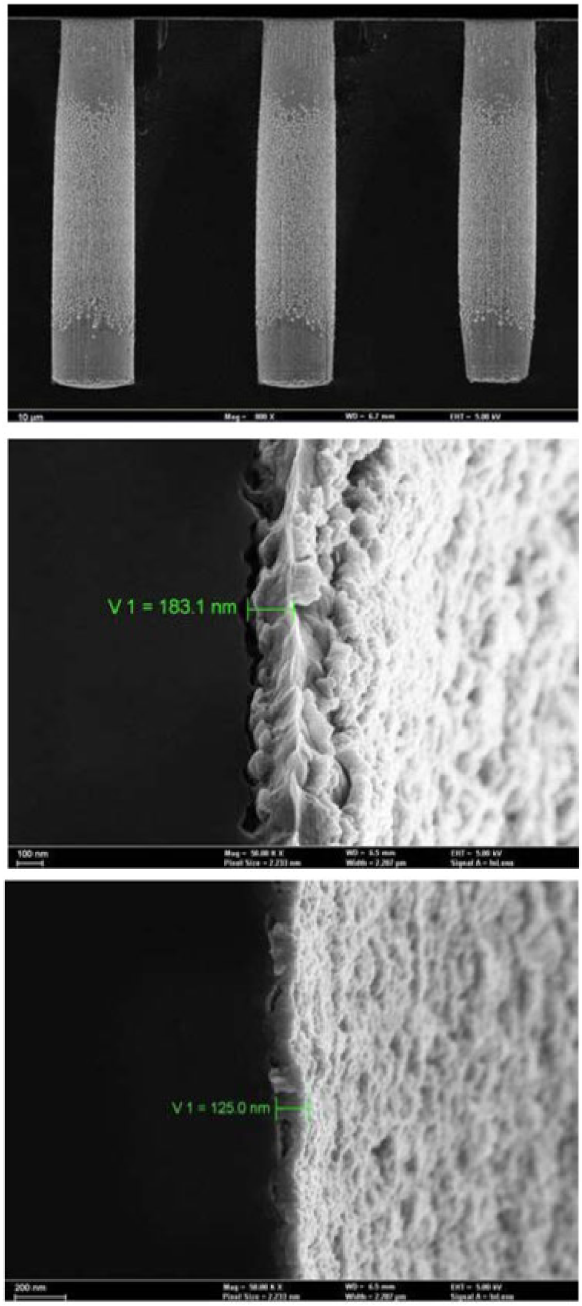
A specific kind of PVD process is that of High Power Impulse Magnetron Sputtering – HIPIMS. In this process, short ($10-100\ \mu s$) impulses having a very high peak power ($0.5-6\ MW$) are delivered to a standard magnetron target, while the average power delivered to the target is kept at a level typical for magnetron sputtering processes (up to $60\ kW$). The high pulse power permits a high ionization of the sputtered material (up to 90%), and for this reason the method is widely used for the deposition of high-density, durable industrial coatings [28] including Diamond-Like Carbon films [29], deep trench filling and TSV structures in the semiconductor industry [30]. The results of TSV metallization performed with an industrial HIPIMS TruPlasma Highpulse 4002 (G2) power supply are presented in Figs. 3a)-c). The high ionization of the sputtered metal obtained with the HIPIMS power supply makes it possible to obtain uniform deposition on the side and bottom walls of the TSV.

C. ATMOSPHERIC PRESSURE PLASMA

Atmospheric Pressure Plasma (APP) overcomes one of the drawbacks of the above-described methods – operation in a vacuum. A process that can take place at ambient pressure eliminates the high cost of a vacuum chamber and its associated components. However, the difficulty of sustaining a glow discharge under atmospheric pressure conditions leads to a challenge, namely, the higher voltages required for the gas breakdown and arcing that occurs between the electrodes. Atmospheric pressure plasma processes can be classified by their electrode configuration, resulting in three types: Dielectric Barrier Discharge (DBD), Corona Discharge (CD), and Plasma Jets and Torches (PJ and PT accordingly), further discussed in [31].

DBD is generated between two electrodes where at least one is covered by a dielectric material. Thus, the plasma formed in the working gas fills the whole space between the positive and the negative electrode. Depending on the operating conditions, including the working gas composition, applied voltage and the frequency thereof, a filamentary or glow discharge will dominate. A filamentary discharge is formed by micro-discharges or streamers that develop on the dielectric layer surface. The dielectric layer plays an important role, as it limits the discharge current, thus avoiding a spontaneous transition from a glow discharge to an arc discharge. It is also responsible for the accumulation of electrons, and therefore for the statistically randomized distribution of streamers. Both the distance between the electrodes and their geometry depend on the operating conditions (especially the gas mixture and voltage) and vary from micrometers to a few centimeters.

A CD is a luminous glow around the sharp tip of a conductor, formed by the ionization of the surrounding gas in a highly non-uniform electric field. It occurs when the potential gradient at the sharp tip exceeds a threshold value but is not sufficient to cause a complete electrical breakdown. This phenomenon is unwanted and dangerous in high-voltage systems, but is used in many industrial applications such as electrostatic precipitator (ESP). Electrostatic precipitators, which were developed to remove sulfuric acid fumes from a gas stream, are used in such processes as the manufacturing of steel, paper and cement, as well as in ore-processing industries and as combustion sources in power plants for collecting particulate emissions [33].



a) b) c)

FIGURE 3. Through Silicon Via coated with *Cu* and *Ti* a), coating thickness at top of via b), coating thickness at bottom of via c). Figs. b) and c) show the strong uniformity of the deposited layer, whose thickness varies only from 183.1 *nm* to 125 *nm*, at the top and bottom of the via, respectively.

Finally, a characteristic feature of PJ and PT is that the plasma is ignited and sustained within the plasma source, but extends beyond the region where it is generated and is launched outside the device in the form of what is known as

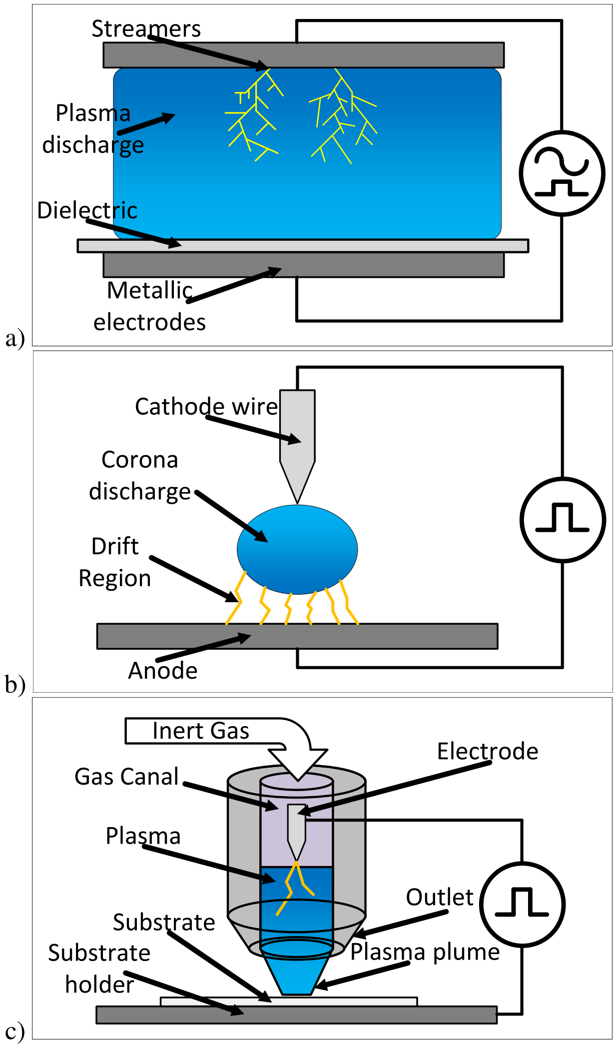


FIGURE 4. **Atmospheric plasma: a) dielectric barrier discharge, b) corona discharge and c) plasma jet [32].**

a "plasma plume". Despite the large variety of configurations, almost all plasma jets structurally integrate an electrode assembly for the generation of the discharge and a channel through which the working gas flows and in which the plasma generates and propagates. Usually the channel has a circular (or round) cross section perpendicular to the direction of the gas flow [32], although ring-shaped or rectangular geometries are also used. The ionized gas from the plasma jet is directed onto a substrate a few millimeters downstream. As the temperature of the ionized gas is low (below $180 - 200°C$) it can be used to etch materials such as plastics or silicon dioxide, as well as in various medical applications including plasma-assisted tissue coagulation and dissection [34], [35].

Since DBD, CD, and PJ sources all differ in their construction, the voltage and power needed in them to ignite and sustain the discharge also vary. CD typically requires a higher voltage of several tens of kilovolts, while DBD typically operates at a lower voltage and power. In contrast, jets benefit from a discharge ignition voltage in the range of those used in magnetron sputtering, below 1 kV.

Fig. 5 shows a summary of the plasma processing techniques discussed above and where they are applied. A detailed description of the power supply types listed below is given in section III.

III. POWER SUPPLIES FOR PLASMA APPLICATIONS

Depending on the application, the maximum average power delivered to plasma ranges from a few watts (e.g. a plasma jet for wound disinfection in medical applications) to more than a hundred kilowatts from a single power supply unit (e.g. large-scale glass coating systems). Moreover, power supplies for industrial plasma material processing applications differ in their control concept, shape and fundamental frequency of output signal or peak output current, depending on the target application, as presented below.

A. TAXONOMY

There are two main approaches to categorize power supplies for plasma processes: by their application or by the shape of their output voltage and current. In the first case, high-performance power converters are divided into the following groups:

- Bias sources,
- Plasma sources (e.g. magnetron, ion sources).

Bias sources are used to introduce a negative DC offset between the substrate and the reference electrode, typically the chamber walls at ground potential, in order to accelerate ions from the plasma to the substrate. This feature is commonly used to increase the film density and deposition rate in thin-film growth, to decrease the roughness of a sputtered film, or to increase the etch depth in semiconductor manufacturing [36], [36]–[38]. As presented in Table 5, DC or Pulsed DC Bias sources are mainly used where electrically conductive substrates feature. In such cases, the power converter has to act as a nearly ideal voltage source with voltage ripples of less than 1% in order to increase the homogeneity of the electrical field, which is essential for growing high quality, uniform films. For more challenging dielectric substrates, it is possible to exploit the plasma's self-bias property and introduce a precisely controlled bias voltage with an RF power generator.

Power supplies used as plasma sources (e.g. magnetron sources, arc sources, ion beam sources, etc.) have to act as a nearly ideal current source. Key features of such power supplies are their ability to shut down output current in microseconds and to suppress arcing. The generic root cause of arcing is poisoning – the growth of a dielectric layer on the target surface or the surface of the biased substrate. As the plasma process goes on, a thin insulating layer made of a compound of the target material (such as aluminum) and the process gas (such as oxygen) is deposited, for example, on the target surface. A dielectric film is typically sputtered (or removed from the target surface) more slowly than a pure metal, and accumulates an electric charge. As the electric field across the dielectric film increases, any local distortion

Industry	Example	Plasma process		Power Supply	Ref.
Decorative Coating	Surface metalization (e.g. metal, ceramic, plastic surfaces)	PVD	cleaning	Bipolar, HiPIMS, RF, Pulsed DC, Pulsed DC + Reverse	[7]-[9]
			etching		
			deposition		
Biotechnology	Microbial decontamination and disinfection	DBD	UV generation	MF, RF	[11]
	Wound disinfection	PJ			[34]-[35]
	Protective layers for joint implants	PVD	deposition	RF	[2]
Glass Coating	Anti-reflective and anti-fog coatings	PJ	deposition	Bipolar/MF, RF, VHF	[5]
	Low-E coatings for architectural glass	PVD			[3]
	UV shields on transparent plastics	PECVD			[4]
Photovoltaics	Silicon wafer surface treatment	PECVD	deposition	Bipolar/MF, RF	[24]
		PVD+CVD	Reactive Ion Etching		
	Transparent conductive oxides	PVD	deposition		
Semiconductor Industry	Through-Silicon Vias	PVD	etching	RF	[21]
		PVD+CVD	Reactive Ion Etching		
	Nanocarbon thin film deposition and patterning	PECVD	deposition		[22]
		PVD+CVD	Reactive Ion Etching		
	GaN surface treatment	PVD+CVD	Reactive Ion Etching		[23]
	Deep in-trench filling	PVD	deposition	HiPIMS, RF, Bipolar, DC	[30]
	Hazardous waste disposal	PECVD	gas abatement	RF, DC	[19]
	Diamond Like Carbon films	PVD	deposition	Pulsed DC, HiPIMS, RF	[29]
Hard & Industrial Coatings	Reflective surfaces (e.g. car lights, industrial mirrors)	PVD	deposition	HiPIMS, DC, Pulsed DC	[6]
	Surface hardening (e.g. drills, engine parts)	PVD	cleaning	DC, Pulsed DC, Bipolar	[1],[28]
			deposition	Arc, HiPIMS	
		PECVD	etching	DC	
Display	LCD screen manufacturing	PECVD	deposition	RF	[18]
Textiles	Hydrophobic textiles manufacturing	DBD	surface activation	DC, Pulsed DC, MF	[12]-[13]
	Dye activation				

FIGURE 5. Sample applications of plasma processing techniques.

of the electric field can lead to an uncontrolled discharge – an arc. Moreover, an untreated arc can seriously damage the target, leading to an abrupt, unplanned stoppage of the production process for target maintenance. This issue is further discussed in subsection III-B.

If power supplies for plasma applications are categorized by the shape of their output voltage or current and their fundamental frequency, as in Fig. 22, the following groups emerge:

1) Direct Current sources (DC),
2) Pulsed Direct Current sources (Pulsed DC),
3) Medium Frequency sources (MF and Bipolar),
4) Radio Frequency (RF) and Very-High Frequency (VHF) sources.

DC power supplies have a broad range of applications. They provide a constant, low-ripple current (in plasma source applications) or voltage (in bias source applications), and are used for substrate heating, electrostatic chucks for wafer positioning, high-voltage sources for atmospheric plasma discharges, and in many other applications.

Pulsed DC power supplies are used as plasma and bias sources. The main difference between a Pulsed DC and a DC power supply is the ability of a Pulsed DC supply to perform a fast ON and OFF sequence so as to produce rectangular waveforms of output voltage and current. The application of pulsing and a regulated duty cycle is used to minimize the probability of arcing due to target poisoning. In a Pulsed DC sputtering process, a short off-time allows for the neutralization of the positive charge accumulated on the surface covered with the dielectric film during the on-time. The efficiency of mitigating arcing by Pulsed DC can be further increased by the application of a so-called *"reverse voltage"*. The above-mentioned benefits of pulsing and reverse voltage are also utilized in bias applications of Pulsed DC power supplies.

Another group of power converters for plasma processing applications is that of medium frequency sources. Low-power supplies are used, e.g., for solar panel manufacturing, while 120 kW generators find application in large-scale systems for architectural glass coating (Fig. 5). The main difference between MF/Bipolar and other types of plasma power supplies is their design; they have two independent output terminals, which may or may not be electrically grounded. Therefore, in magnetron sputtering applications they are typically used in a dual magnetron arrangement where both output terminals are detached from the electrical ground. Such an electrical configuration results in the target alternately functioning as cathode and anode, depending on the actual polarization of each of the power supplies' output terminals: when one of the outputs is polarized negatively to perform sputtering, the other one is acting as the anode. After one half-period, the electrical conditions are reversed, and the first target is now the anode while the sputtering process continues on the second target.

There are two main types of medium-frequency power supplies: MFs, which provide an alternating sine-wave output signal, and Bipolar units, where the shape of the output signal can be modified to achieve a rectangular, triangular or trapezoidal waveform. The ability to modify the current and voltage waveform shape during normal operation, without additional mechanical changes, makes it possible to manipulate the average plasma ion energy, which is essential for the deposition of oxygen-based films (e.g. SiO_X, ZnO_X, GaO_X) [39], as in these applications, too high a kinetic energy of O^- ions may result in an undesired damage to the deposited film [40]. Moreover, bipolar power supplies can introduce an off-time (or break time) separating subsequent pulses, which gives additional time for the electrons to reach the surface of both targets and – as a result – to discharge the surface of those electrodes before the next pulse. This allows for a significant arc rate reduction, as presented in Fig. 6, thus stabilizing the process and improving the uniformity of the sputtered layer.

The last major group of power supplies used for plasma processing are RF and VHF power supplies. In particular, 13.56 MHz and its harmonics are the most typical operation frequencies reserved for industrial and medical applications. Depending on the application, RF power can be generated by applying an RF voltage across two parallel electrodes installed in a vacuum chamber (Capacitively Coupled Plasma – CCP) or by circulating RF currents in a coil mounted on the outside of the vacuum chamber and separated from the plasma by a dielectric window (Inductively Coupled Plasma – ICP). Both methods transfer the energy of the RF electromagnetic wave to the electrons in the plasma to sustain the discharge.

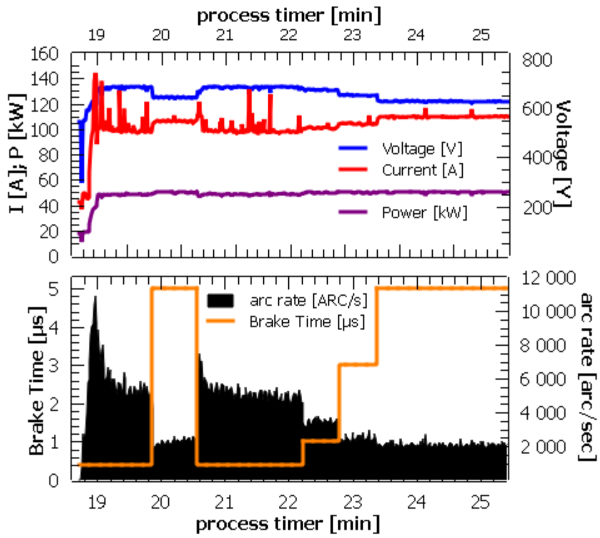


FIGURE 6. Process parameter log presenting impact of additional off-time between positive and negative pulses (orange line marked as *Break Time*) for arc rate (black bar graph) for constant operating conditions (power supply output voltage, current and power presented in the upper graph).

CCP and ICP have been used for several decades for the deposition and etching of thin films, especially in the fabrication of microelectronics. In CPP systems, the substrate to be etched is usually placed on a powered electrode and the RF power provided simultaneously controls the ion flux to the substrate and the energy with which the ions arrive. To separately control the ion flux and energy, dual-frequency CCP systems have been introduced. Alternatively, ICP systems are used where two RF power supplies are also necessary: an RF plasma generator operating on an ICP coil to generate plasma ions, and an RF bias power supply connected to the substrate holder to control the ion energy. To provide an ion flux of the required energy, the frequency of the ICP source has to be equal or higher than the RF bias generator. For instance, two 13.56 MHz RF power supplies might be used, or a 13.56 MHz as ICP plasma source and a 0.4 MHz as a the bias source.

It is rare to compare the performance of different types of power supplies for plasma processing, such as an RF power supply versus an HiPIMS, due to fundamental differences in their operating conditions, e.g. the configuration of the vacuum system or the properties of the sputtered material. It is, however, common in the plasma industry to compare power supplies from various vendors as part of the qualification process for a new vacuum system. Regardless of whether different (e.g. Pulsed DC vs DC) or the same type (e.g. Pulsed DC vs Pulsed DC) of power supplies are compared, such investigations always focus on process parameters or the physical properties of the manufactured layer, including resistivity, refractive index, extinction coefficient, corrosion resistance, hardness and others. Typical examples of process-related KPIs used are:

1) etch or deposition rate per process,
2) arc rate during process,

The etch rate indicates the thickness of a removed layer per defined period of time, and is commonly used to assess efficiency. High etch rates are greatly desired, as they make it possible to cut down the plasma processing time, significantly increasing production line throughput and reducing the final cost of the manufactured device. Arc rate indicates how many arcs occurred during the process. As arcing is highly undesirable in magnetron sputtering or dry etching processes, the lower the arc rate, the better. Examples of comparative studies of DC, Pulsed DC and Bipolar power supplies used for the sputter deposition of a transparent conductive oxide are given in Fig. 7. Figure 7a) shows that Pulsed DC power supply provides a significantly higher deposition rate than a DC power supply. Thus, within the same process duration, the layer deposited with a Pulsed DC power supply is thicker than that deposited with a DC power supply, resulting in significantly higher electrical resistivity. Comparative study data obtained with Bipolar power supplies are presented in Fig. 7b) and indicate that the deposition rate obtained with a power supply from vendor #1 was more than twice that obtained with a power supply from the other vendor. The process was repeated for both 800 W and 1200 W to verify the consistency of the test results. As presented in Fig. 7b), the test at 1200 W also favored power supply from vendor #1.

B. CHALLENGES AND REQUIREMENTS FOR POWER CONVERTERS IN PLASMA APPLICATIONS

A fundamental requirement for any power supply for plasma processing is its ability to *ignite* the plasma. Typically, the glow discharge used in industry requires only $300 - 600\ V$ to be sustained, depending on the gas pressure and composition, the distance between the electrodes, and other process parameters. Unfortunately, for ignition itself, which is in fact, a transition of a dark discharge into a glow discharge, the voltage applied to the plasma chamber has to be significantly higher – up to $1500 - 2000\ V$, as shown in Fig. 8. This fact has a significant impact on the design of power supplies for plasma processing, as it favors the use of multilevel converters or high-voltage semiconductor devices. Therefore, Si or SiC components are more suitable than GaN devices because they have a higher voltage rating: $1.2 - 1.7\ kV$ for Si/SiC devices and 650 V for GaN, respectively. If the output stage of the power supply for plasma processing is not capable of igniting the plasma by itself, it is possible to use an auxiliary ignition module – e.g. a spark generator [41]. The process of plasma ignition becomes more complicated if the frequency of the applied voltage increases, as in the case of RF and VHF power supplies. These systems are subjected to wave phenomena, such as load mismatch or forward and reflected voltage waves. If the plasma is not ignited by the auxiliary

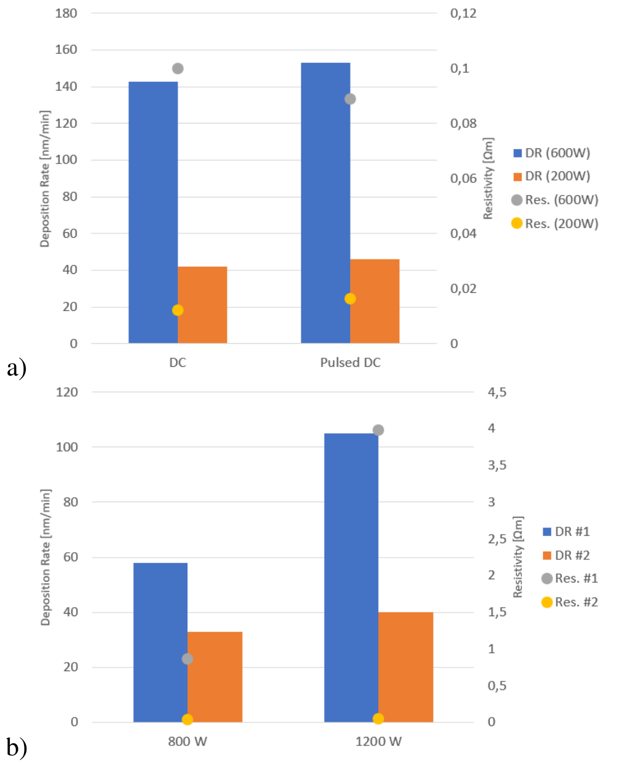


FIGURE 7. **Comparative study of transparent conductive oxide layer deposited on glass panel with DC and Pulsed DC power supply a) and two Bipolar power supplies b). Acronyms used in this figure: "DR" - deposition rate, "Res" - resistivity.**

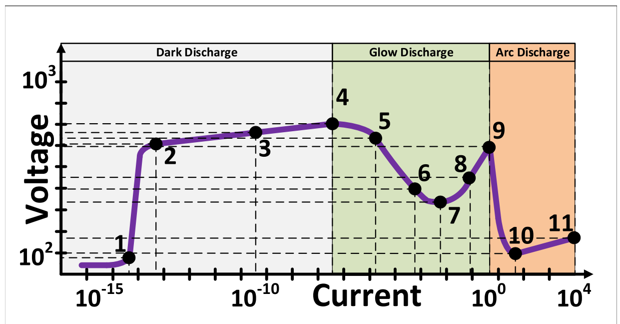


FIGURE 8. **Typical Voltage-Current characteristic of an electrical discharge. Characteristic regions marked as follows: 1- random pulses caused by cosmic radiation, 2- saturation current, 3- avalanche Townsend discharge, 4- self-sustained Townsend discharge, 5- corona discharge, 6- sub-normal glow discharge, 7- normal glow discharge, 8- abnormal glow discharge, 9- glow-arc transition, 10- arc discharge, 11- electric arc.**

module, the power supply just has to withstand full-reflection conditions long enough until ignition occurs.

One of the key features of plasma sources is their ability to detect and suppress arcing. From the electrical point of view, a transformation of a magnetron discharge to an arc is an abrupt decrease in voltage (e.g. by 50%) with an instantaneous increase in current (e.g. by 100%), as is presented in Fig. 9. Within these several microseconds, a remarkable amount of energy (E_{arc}) is transferred into the arc, that is, the product of the voltage applied to the target ($v_{out}(t)$), the current delivered to the arc ($i_{out}(t)$), and the arc persistence time ($t_{arc} = t_1 - t_0$), as is presented in equation 1.

$$E_{arc} = \int_{t_0}^{t_1} (v_{out}(t) \cdot i_{out}(t))dt \quad (1)$$

Equation 1 shows that a key factor for successful arc handling is an ultra-fast (within microseconds) detection and suppression of the output current, which implies challenging requirements for the output voltage/current measurement circuit, the analog to digital signal conversion layer, the digital signal processing algorithm or the arc detection algorithm itself. To fulfill this requirement, it is common to use ultra-high-speed operational amplifiers, fast Analog-to-Digital (ADC) and Field Programmable Gate Arrays (FPGA), or System-On-Programmable-Chips (SOPC) for electrical-based arc management [42]. Although it is possible to use a rather slow measurement circuit for arc detection, such a solution would not be sufficient for Pulsed-DC or MF/Bipolar systems, where the output signal frequency may vary from 1 kHz to 150 $-$ 300 kHz. An example of an arc detection based on electrical measurements is presented in Figs. 9a) and 9b). In both examples, the arc caused an instant disruption of the power supply output voltage (blue line) and a linear increase in the output current (red line). As shown in Fig. 9a), the arc detection algorithm based only on the current measurement had a significantly longer reaction time than the algorithm based on both voltage and current. An alternative approach typical of cheap and simple power supplies is to use a current-controlled power supply, e.g. one operating in current-mode [43] or cascaded voltage and current controllers (with and without feedforward) [44]. Unfortunately, in some applications, only voltage-controlled sputtering can be successfully utilized [45]. Moreover, due to their design, instead of shutting the arc off, current-controlled power supplies sustain it at a certain level, since no feedback on whether the output current is conducted through the plasma or the galvanic shortcut on the cathode, is given to the control algorithm, as shown in Fig. 10.

Another aspect of proper arc handling is the restart operation after an arc, as depicted in Fig. 11. The power supply has to be able to fully restore the desired output power immediately after the arc handling in order to maximize process efficiency and the quality of the deposited layer. Thus, long breaks in operation and slow-slope ramping after an arc are undesirable because they decrease the average power delivered to the chamber and, as a result, decrease the deposition rate and other key process quality indicators. This requirement favors fast dynamic response control algorithms and power converter topology.

Understandably, arc detection becomes even more challenging in the case of RF and VHF power supplies, due to the very high operational frequency of their output voltage or current. Therefore, in high-frequency systems different methods are utilized, such as: monitoring RF forward; reflected power [46]- [47], which requires the use of a directional coupler in the power supply; harmonics analysis [48], which requires the implementation of sophisticated signal processing circuits and an algorithm; or even an analysis of the acoustic emissions in the plasma chamber [49], which requires the use of additional probe systems.

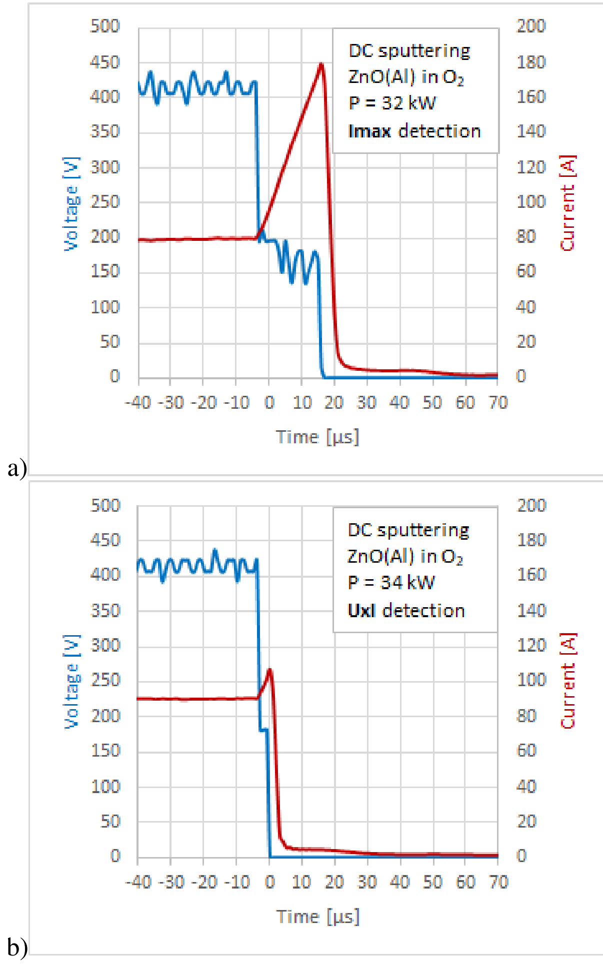


FIGURE 9. Sample current (red) and voltage (blue) shapes during a hard arc detected with only current-based detection criteria (a) and current- and voltage-based detection criteria (b).

Another key requirement is the reliability and robustness of HPPS, since such devices are usually utilized in complex manufacturing processes. Because the typical end product (e.g. a polarization filter on a camera lens, an integrated circuit) is a stack-up of tens or hundreds of ultra-thin layers of specific compounds, plasma processes are performed in multiple runs. In each stage of the process, a different mixture of gases is injected into the plasma chamber to build up a nanometer-thin layer. Typically, 50 $-$ 250 layers may be required to achieve the desired properties. If only a single step were to be interrupted, e.g. by a power converter failure, the sputtered layer would be distorted, which might significantly change the properties of the whole stack-up, resulting in a waste of the whole batch.

A further challenge is the integration of multiple power supplies within a single plasma processing system. As an example, in many applications power supplies are subjected to pulsed operating conditions. Therefore, to increase the

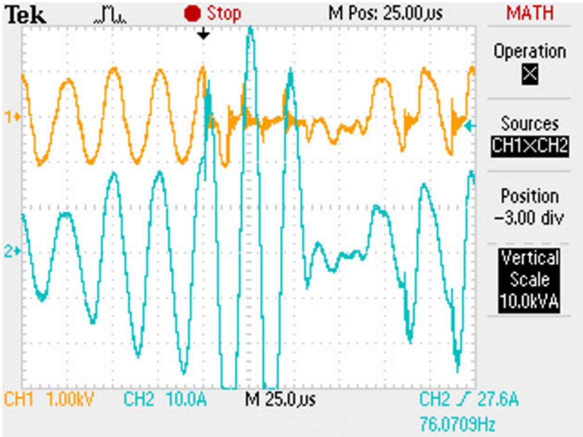


FIGURE 10. **Voltage (yellow) and current (blue) shapes during a hard arc handled by a current-controlled power supply. The galvanic short circuit between the output terminals was not properly detected and the current increased until the overcurrent protection switched off the output module.**

deposition rate and improve the stability of the process conditions, it is necessary to synchronize the pulses or arc management algorithms between power supplies, e.g.:

- bias and source RF power supplies in single- and dual-frequency systems [18]
- bias and source Pulsed DC power supplies in PVD systems,
- multiple source Bipolar power supplies in dual magnetron sputtering systems [50],
- and many others.

Since a pulse period may vary from $1 - 0.1$ $[ms]$ to $8 - 2.5$ $[\mu s]$ depending on the application, and since arcs occur randomly, the synchronization protocol between the power supplies must have almost no propagation delay. Therefore, typical complex communication protocols such as EtherCat TM, Profibus TM, DeviceNet TM , and others are inadequate for this purpose. Commercial solutions for synchronization often use digital signals or an external clock signal, transmit via either fast parallel communication lines or a coaxial cable, and are processed by FPGA systems. This seriously impacts the design of both the control board and the control algorithm of the power supply for the plasma material processing application.

The last fundamental requirement for all the types of the power supplies discussed here is the ability to ground one of the inputs. In a typical unipolar application, the positive or negative output of the DC/Pulsed DC power supply is tied to the electrical ground by being connected to the plasma chamber itself, depending on whether the user needs a negative or positive voltage across the cathode. Therefore, at least one stage of energy conversion has to assure galvanic insulation between the input and output terminals. Because there is constant pressure from the plasma processing industry to increase the volumetric and gravimetric power density of power supplies, this requirement is driving the development of high-frequency power transformers.

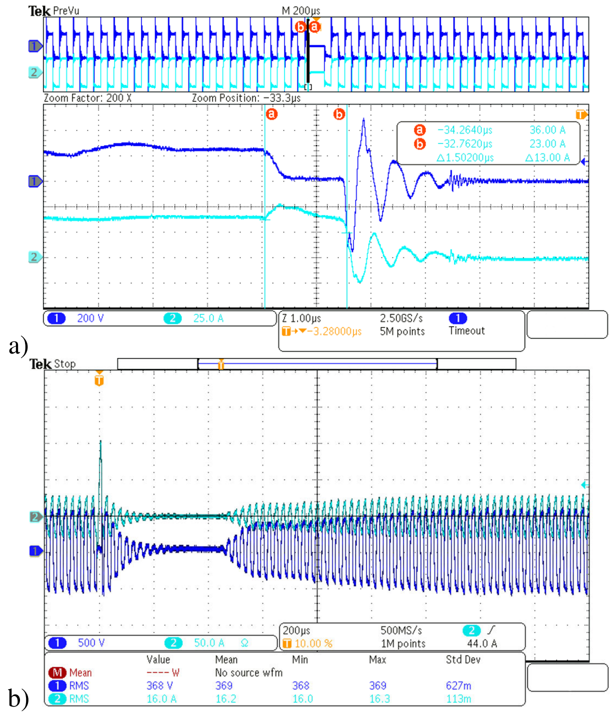


FIGURE 11. **Arc handling and restoration performed by a state-of-the-art power supply a) and a simple, cheap, current-controlled inverter for plasma processing applications. Channel 1 (dark blue) – output voltage, channel 2 (light blue) – output current.**

C. POWER CONVERTERS TOPOLOGIES

Power supplies for plasma processing applications are usually complex, modular systems with multiple energy conversion stages, as presented in Fig. 12. Various types of power converters may be found that are suitable to be used in such power supplies, but in different plasma processing applications. Therefore, any comparative study of the basic types of power converters should take account of the potential usage of these devices in the same functional module of the power supply for the plasma processing application. The following assessment method is therefore proposed – each type of power converter can be identified as:

- well suitable,
- suitable,
- not suitable,

for following target application:

- input stage of power supply for plasma processing,
- interlink stage of power supply for plasma processing,
- output stage of power supply for plasma processing.

Typical Key Performance Indicators (KPI) used for comparing various designs of Power Factor Correction (PFC) modules are:

1) total harmonic distortion on input current,
2) total harmonic distortion on input voltage,
3) power factor,
4) efficiency,
5) total cost.

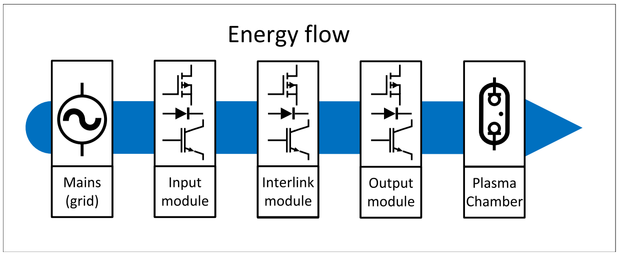


FIGURE 12. Simplified block diagram of a typical power supply for plasma processing with energy flow direction marked.

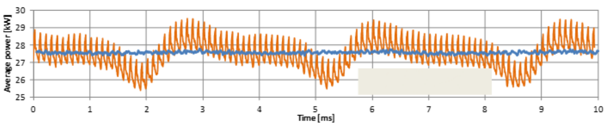


FIGURE 13. Example profiles of the average power delivered to a plasma chamber, measured using a MATH function in a digital oscilloscope as a multiplication of the power supply output voltage and current. The orange trace indicates the presence of both high and mains frequency fluctuations, which makes such power supply sub-optimal for plasma processing applications. The blue trace shows a proper average power envelope during the plasma process.

		Efficiency	THD_V Reduction	THD_I Reduction	Wide Range Operation	Active components		Measured Currents	
						1f input	3f input	1f input	3f input
Bridge - based	Resonant Converters	<98%	Good	Poor	Poor	4	4	1	1
	Boost	95.68%	Good	Poor	Good	1	1	1	1
	Buck	95.8%	Good	Poor	Good	1	1	1	1
	Interleaved Boost	97.6%	Good	Poor	Best	2	2	2	2
	SEPIC	91.95%	Good	Poor	Best	1	1	1	1
Bridgeless	Totem Pole	<98.6%	Good	Poor	Good	2	8	1	4
	Active Bridge	<98%	Good	Good	Good	4	6	1	3

FIGURE 14. Comparison of typical power converter topologies used in either single-phase or three-phase PFC circuit.

However, in plasma surface processing applications, these KPIs are insufficient, and two additional indicators have to be defined:

7) main frequency power fluctuations seen at the output of the power supply,
8) immunity for pulsed operating conditions [51].

Indicators 1)-5) are rather typical for all electronic equipment, as they are fundamental for power quality improvement and economic evaluation. However, the strict limits on the presence of the mains frequency in the output signal are unique to plasma processing among industrial applications. Low-frequency fluctuations, shown in Fig. 13, disqualify a power supply's design from bias applications because these impact the plasma properties, including the ion energy density, which can lead to a deterioration in the quality of the coating. A closer analysis of Fig. 13 shows that the orange trace consists not only of 300 Hz fluctuations caused by the improper design of the input module, but also of $\sim$ 10 kHz ripples from the output buck converter. In contrast, the blue trace measured from the power converter of a different design shows no significant ripples or fluctuations.

A typical design of an input module is a simple bridge rectifier with a unidirectional boost converter, as presented in [52], [53], although other hard-switching converters (e.g. interleaved boost converter [54] or a buck converter [55]) can also be successfully utilized. Moreover, various researchers have proved that resonant converters (e.g. LLC, LCC) can also be used in such configurations [56], although the design of a wide input range resonant converter, which is immune to voltage sags and other grid events, is far more challenging than in the case of a hard-switching topology. Thus, in the scope of a wide-range operation, a non-inverting buck-boost or SEPIC topology [57] outperforms other converters, as it can provide either a higher or a lower voltage on the output terminals than on input. Although typical buck-boost or Cuk converters also have similar properties, they invert the output voltage polarity, which can cause additional design issues. Recently, bridgeless designs (e.g. bridgeless boost, totem-pole PFC, bidirectional boost converter, active bridge [58], [59] have become increasingly popular in industrial and automotive applications [60], for being more efficient than bridge-based solutions, achieving rates of 97.5% – 99% [61], [62]. Moreover, an improvement in efficiency has been proved for both single-phase and three-phase designs [60], [63]. An active bridge topology stands out among the above-mentioned designs in terms of KPIs 1) and 2), as state-of-the-art control algorithms (e.g. space vector modulation [64]) permit a significant reduction in either current or voltage total harmonic distortion. On the other hand, active bridge and totem-pole designs require far more active components than bridge-based input models, as presented in Fig. 14.

Various researchers have proved that a single-stage LLC resonant converter [65], [66], an LCC resonant converter [67], [68], a semi-soft switching converter [69], [70] or a hard switching converter [53] are all well suited as intermediary power conversion systems. Therefore, these types of power converters could be easily adapted for the purposes of forming an interlink for every type of power supply for plasma processing. Although modular or multilevel converters [71], [72] can also be successfully utilized as an interlink in any plasma power supply, such power converters are better suited to HV applications, as using a multilevel converter in a low-voltage source may prove to be sub-optimal in terms of Design to Cost [73] or Design for Reliability [74] methodology.

However, in some designs, the input and interlink modules are combined into a single functional module. Then, performance evaluation should focus on the KPI defined for input modules.

As shown in Fig. 22, almost every power converter topology is applicable at the output stage of a DC power supply. Of course, no topology is universal, nor is any solution suitable for every application. Therefore, any decision on the design of a DC power supply for plasma processing should be supported with a detailed analysis of the functional requirements and the power supply application. As an example, a resonant converter (e.g. LLC or LCC) is a good choice for

	Active components	ZVS	ZCS	REF
LLC	2S – 4D	YES	NO	65 - 66
LCC	4S – 4D	YES	NO	67 – 68, 72
ZCS Full Bridge	5S – 4D	NO	YES	70
Dual Full Bridge	6S – 2D	YES	NO	69
PFC + Full Bridge	5S – 3D	YES	NO	71

FIGURE 15. Composition of semiconductor devices in power converter topology suitable for interlink stage applications.

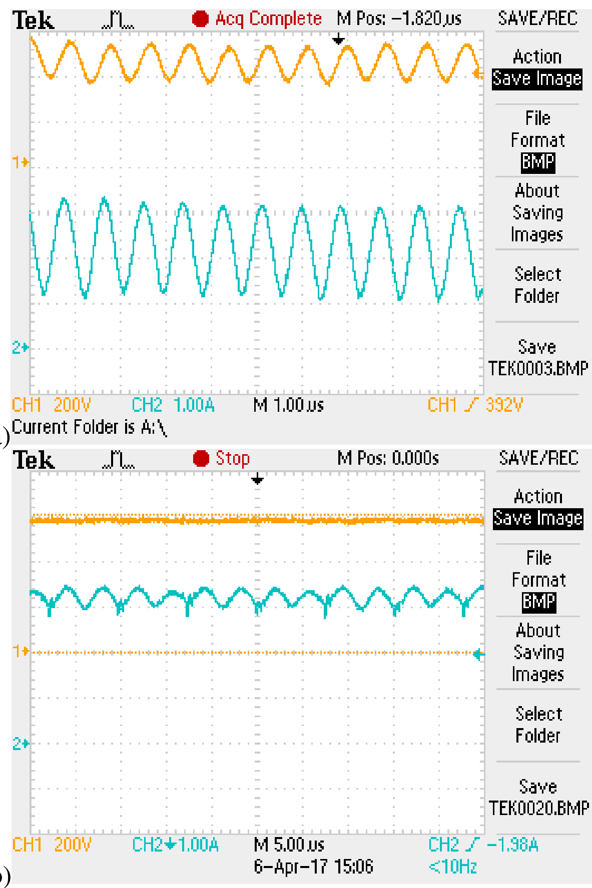


FIGURE 16. Performance comparison of 20 *kW* DC power supplies equipped with an output module based on a resonant converter and a diode rectifier a) and a buck converter b). Channel 1 (orange) output voltage, channel 2 (blue) output current.

a highly efficient device with a rather narrow linear control range, as in the case of a power supply for resistive heating in epitaxial crystal growth. On the other hand, it would perform poorly as a plasma source with a wide range of linear output voltage and current regulation. For the same reason, resonant converters are inadequate for bias power supplies, because such a topology is not optimal for idle work, typical of bias applications. Such power supplies usually operate with a

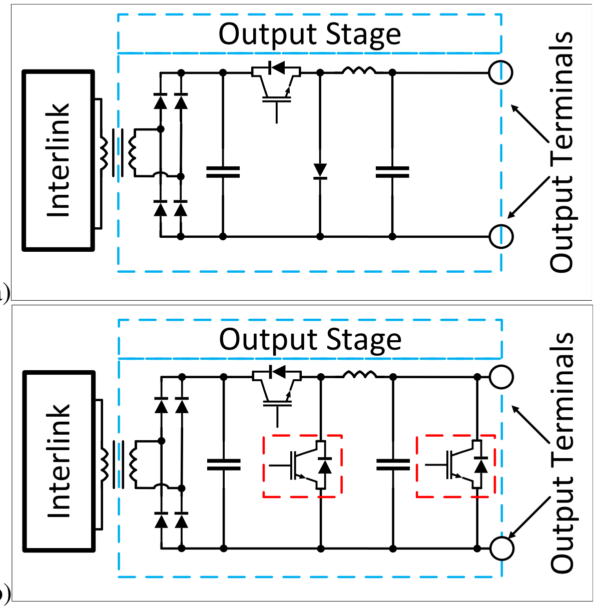


FIGURE 17. Comparison of output stage for a DC plasma source for magnetron sputtering [79] (a) and a Pulsed-DC bias source for a CVD system [78] (b). A typical configuration of the electronic switch shorting output terminals is marked with a red dashed line.

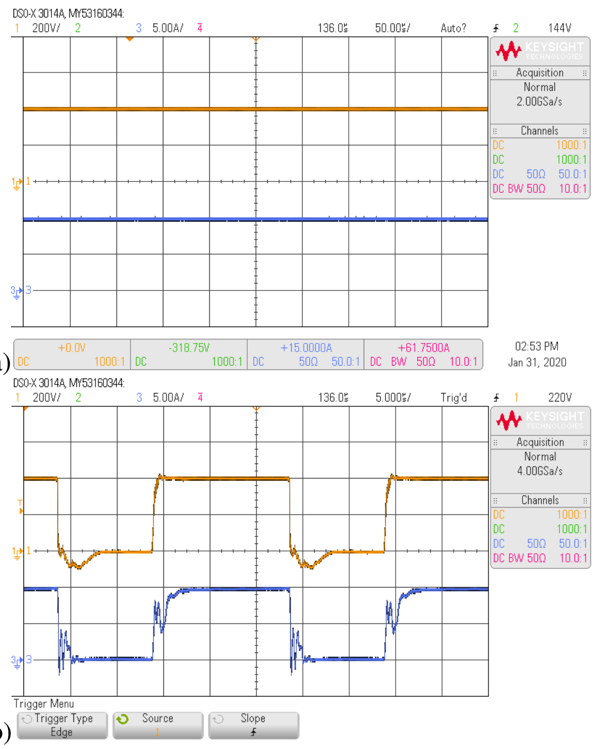


FIGURE 18. Output voltage (yellow, upper) and current (blue, lower) of 20 *kW* bias power supply in a DC mode a) and Pulsed DC mode b). Timescale - 50 $\mu s/div$, channel 1 - 200 V/div, channel 3 - 5 A/div.

high output voltage but very low current. To emphasis the difference in performance between a resonant converter and a hard-switching converter operating at a low load, a comparison of two 20 *kW* DC power supplies is presented in Fig. 16. Although both power supplies operated at ∼ 15% of

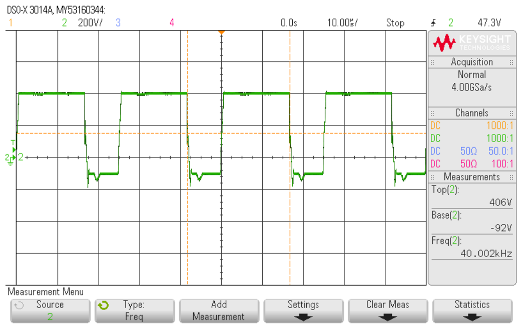


FIGURE 19. Output voltage (yellow, upper) and current (blue, lower) of 20 kW bias Pulsed DC power supply with Reverse. Timescale - 10 $\mu s/div$, channel 2 - 200 V/div.

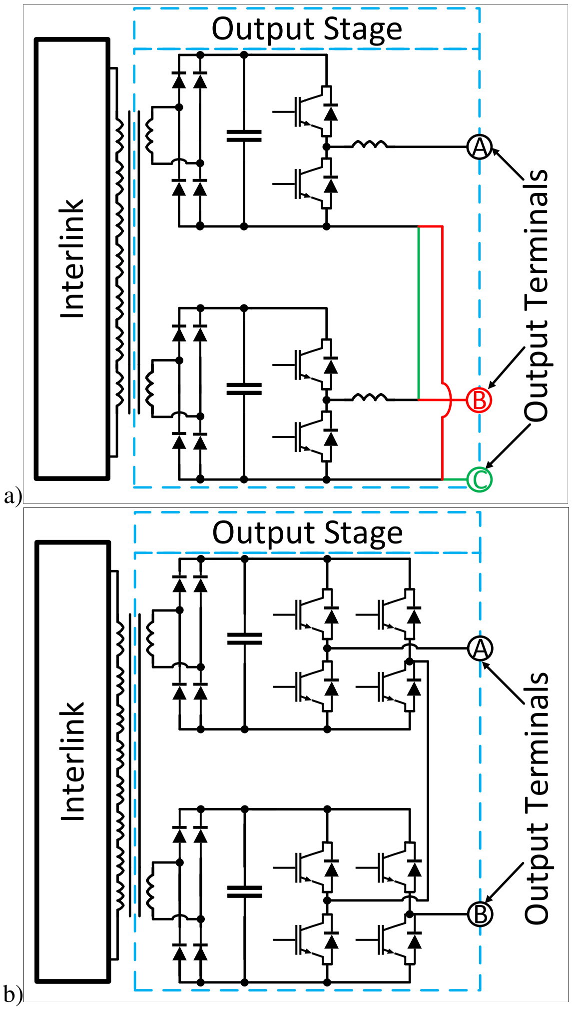


FIGURE 20. Comparison of output stage for Pulsed DC plasma source with reverse voltage a) and Bipolar plasma source [81] b). There are two typical configurations of output terminals for power supplies with Reverse voltage: $A-B$, marked with black-red line [84] and $A-C$, marked with black-green line [82].

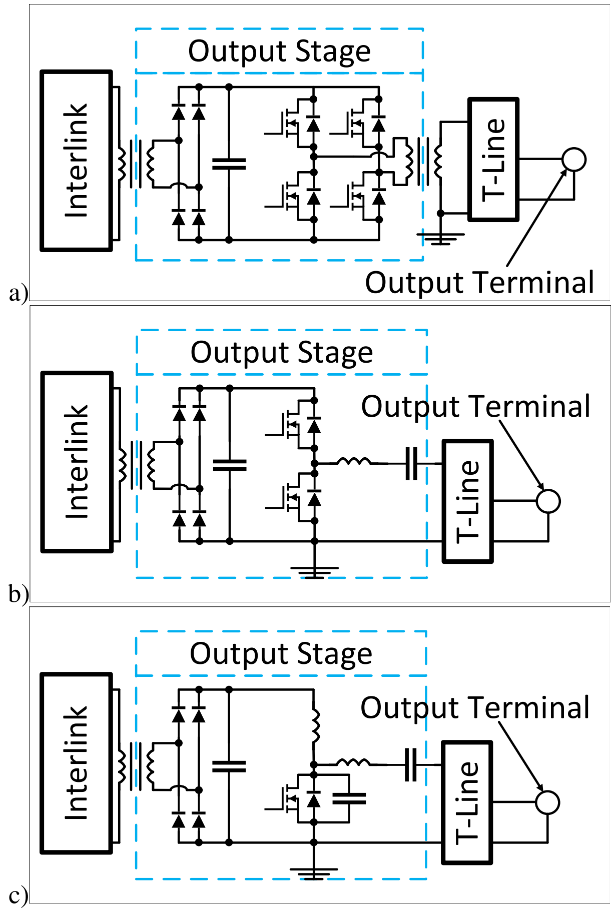


FIGURE 21. Typical resonant converters used in high frequency power supplies for plasma processing (a) class D [91], (b) class DE (modified D) [90] and (c) class E amplifier [93].

nominal power, the resonant converter (Fig. 16a)) exhibited significantly higher output voltage and current ripples than the hard-switching topology (Fig. 16b)).

As in the case of an interlink, multilevel converters are a good choice for a high-voltage application (e.g. CD, DBD), while using such a topology in a low-voltage application (e.g. arc sputtering, arc welding [53], [71]) could be simply inadequate. Here, a single-stage hard-switching power converter is often an appropriate solution [75].

In the case of a Pulsed DC power supply, the device architecture has to be able to shut off the voltage and current within microseconds to achieve a 'rectangular' signal shape. Therefore, the output stage of such a power supply needs to have either a very low output capacitance [76] or the ability to short both output terminals with a controlled electronic switch [77], [78]; this favors topologies such as, e.g., a synchronous buck converter. For better clarification, a comparison of the output stages of a simple DC and a Pulsed DC power supply for plasma processing is presented in Fig. 17.

Sample voltage and current waveforms of a DC and a Pulsed DC power supply are presented in Fig. 18. To achieve such a high di/dt and du/dt slope, the power supply has to be able to extract the energy stored in the parasitic inductance of the cables connecting it to the cathode (the sputtering target). For this purpose, a slightly negative voltage may be introduced at the end of each pulse [80], as presented in Fig. 18b).

The choices become much more limited for Bipolar and MF supplies, or Pulsed DC supplies with Reverse Voltage, since such devices:

Typical parameters and output voltage shape of power supplies for plasma processing	Single Stage Converters: Resonant Converters – LLC	Single Stage: Resonant – LCC	Single Stage: Non-Resonant Converters – Semi-Soft Switching	Single Stage: Non-Resonant – Hard Switching	Modular and Multlevel Converters: Resonant Converters – LLC	Modular/Multilevel: Resonant – LCC	Modular/Multilevel: Non-Resonant Converters – Semi-Soft Switching	Modular/Multilevel: Non-Resonant – Hard Switching	
DC P_{AV} 1–60 kW, V_{OUT} 0.4–25 kV	Well Suitable				Suitable				**Input**
	Well Suitable								**Interlink**
	Suitable			Well Suitable	Suitable			Well Suitable	**Output**
Pulsed DC P_{AV} 1–180 kW, V_{OUT} 0.4–1.5 kV, f_{PULSE} 1–300 kHz	Well Suitable				Suitable				**Input**
	Well Suitable								**Interlink**
	Suitable			Well Suitable	Suitable			Well Suitable	**Output**
Pulsed DC w. Rev. P_{AV} 1–180 kW, V_{OUT} 0.4–1.5 kV, f_{PULSE} 1–300 kHz, V_{REV} 20–200 V	Well Suitable				Suitable				**Input**
	Well Suitable								**Interlink**
	Not Suitable			Suitable	Suitable			Well Suitable	**Output**
HiPIMS P_{AV} 40–60 kW, P_{PEAK} 1–6 MW, f_{PULSE} 1–10 kHz, V_{OUT} 1.2–2.5 kV	Well Suitable				Suitable				**Input**
	Well Suitable								**Interlink**
	Not Suitable				Suitable			Well Suitable	**Output**
BiPolar/MF P_{AV} 40–180 kW, V_{OUT} 0.4–1.5 kV, f_O 1–150 kHz	Well Suitable				Suitable				**Input**
	Well Suitable								**Interlink**
	Not Suitable							Well Suitable	**Output**
RF P_{AV} 1–120 kW, f_O 0.4–200 MHz, Z_{OUT} 50 Ω	Well Suitable				Suitable				**Input**
	Well Suitable				Suitable				**Interlink**
	Not Suitable		Well Suitable	Not Suitable			Well Suitable	Not Suitable	**Output**

FIGURE 22. Cross comparison of main types of power converters and their potential applications.

- need to be able to operate with both output terminals separated from the electric ground,
- need to deliver both positive and negative voltage between terminals.

Therefore, transformer-based power converters, half-bridge converters, full-bridge converters and multilevel converters perform better in such applications, as has been clearly demonstrated by various researchers – [66], [81]–[84]. If necessary, Reverse Voltage can be also introduced by interrupting the current flowing through the choke, as is presented in [85], [86]. Unfortunately, such a solution has a significant disadvantage – the amplitude of the Reverse Voltage is a product of the current flowing through the choke, which is dependent on the load impedance and on-time, and is therefore uncontrolled. Here, a transformer-based design or multilevel converter makes it possible to achieve an easily controlled, rectangular shape of reverse voltage, as shown in Fig. 19. Examples of typical solutions for the output stage of Bipolar or Pulsed DC power supplies with Reverse voltage are presented in Fig. 20.

In the case of High Power Impulse Magnetron Sputtering, the power supply has to deliver extremely high power to the cathode in a very short pulse. For such a high current and voltage rating (approximately 1000 A and 2000 V), multilevel and modular converters seem to be the best choice, for they make it possible to keep the voltage, current, and power rating across either electronic switches and passive components at a reasonable level. Moreover, a multilevel and modular approach allows the use of mature, proven components rather than experimental technology, which is critical from the point of view of reliability-oriented design. In an HiPIMS application, a cascaded connection of multiple isolated DC sources (e.g. a cascaded H-Bridge [81]) is the best solution, as it allows for a wide-span output voltage/current control and a sharp voltage slope formation, essential for plasma processing. A similar approach is presented in [87], where a cascaded connection of multiple buck converters was utilized to develop a pulse power supply for high-energy lasers.

Last but not least, due to the very high operating frequency of RF power supplies ($0.4-200$ *MHz*) only soft- or semi-soft switching power converters can be successfully employed. Typical power amplifier classes suitable for plasma processing applications are AB, D, DE, E, F^{-1}, although the AB class is rarely seen nowadays due to its rather low efficiency (up to 70%) [88]–[92]. In contrast, the rest of the above-mentioned power amplifier classes allow for nearly 95% efficiency while maintaining satisfactory spectral purity of the output voltage waveform. As was stated above, a key feature of every power supply for plasma processing applications is their ability to ignite the plasma. In the case of RF and VHF power supplies, to fulfill the above requirement, the voltage amplifier has to be able to withstand operating under a heavily mismatched load, since the process chamber represents an open circuit before plasma ignition. Therefore, the typical Voltage Standing Wave Ratio for this type of power supply is specified as being from ~ 2.62 for nominal operating conditions up to ~ 25 for plasma ignition conditions, and must be achieved with limited power in a short time period. The power converters most commonly used in the output stage of RF and VHF power supplies are presented in Fig. 21.

To sum up the discussion, a graphical cross-comparison of the main types of power electronic converters and their potential application in power supplies for processing plasma materials is presented in Fig. 22.

IV. SUMMARY AND FUTURE CHALLENGES

In this paper, a variety of plasma-based material processing applications were presented. Moreover, the main types of high-performance power supplies for plasma systems were distinguished, and key features of those devices discussed. Finally, a thorough evaluation of the types of power converters commonly used in plasma processing applications was made. It was also shown that the number of reasonable solutions gradually decreases as the sophistication of the plasma process increases. It is therefore expected that the design of future generations of high-performance power supplies will be strongly influenced by the following demands:

- reduced size,
- increased power rating,
- reduced purchase cost,
- reduced maintenance and utilization cost,
- increased integration with other components of the plasma processing system.

Therefore, to reach satisfactory levels of volumetric power density, designers will turn towards Wide Band-Gap (WBG) semiconductor devices (e.g. *SiC* or *GaN* transistors) and higher operating frequencies, especially in the case of input and interlink modules. Although such an approach allows for a significant reduction in the number of passive components, it raises questions regarding useful lifetime, as the reliability of WBG devices is still being studied intensively by various researchers. Moreover, optimizing manufacturing costs will result in a tendency to decrease de-rating levels and to replace oversized devices with tailor-made solutions. This will increase interest in Design for Reliability procedures, e.g. enhanced electrothermal analysis based on a Mission Profile, or more precise estimations of reliability and lifetime modeling. These concepts are often discussed in publications that cover the automotive, aircraft, and grid applications of power electronic converters.

Rising energy prices and stricter power quality requirements will create a tendency to reduce the operating costs of power supplies used for plasma processing. New generation devices will have to improve their wide-range efficiency to reduce power losses and the amount of voltage and current harmonics injected into the grid. The first requirement will encourage designers to frequently use either integrated solutions (e.g. a combined input and interlink module) or resonant converter topology. The second requirement will promote the use of active rectifiers with complex current and voltage algorithms instead of passive solutions.

Reducing maintenance costs will mostly involve increasing reliability and the remaining useful lifetime (RUL) calculation in order to extend the time interval between preventive maintenance procedures. Thus, either health monitoring procedures of a power converter's critical components (e.g. capacitors, semiconductor devices) will be implemented in future generations of HPPS, or RUL estimation will be performed on the basis of precise electrical modeling (e.g. a digital twin). It is expected that a model-based RUL calculation will be used more often than health monitoring in mass-produced power supplies, as it can be successfully implemented without additional measurement circuits, making it a more cost-friendly solution.

The last technical trend that will have an impact on the design of future generations of high-performance power supplies is Industry 4.0. Although concepts like Machine-Machine communication, Cyber-Physical Systems and Cyber-Physical Production Systems will have no impact on power converter design, they will greatly affect both the hardware and software layers of power supply operating systems, since the number of data streams processed by a power supply will increase. And so it is expected that future challenges will be related to the successful implementation of broadband communication solutions – e.g. fiber-optic communication or a 5G local area network. Furthermore, "Industry 4.0 compliant" power supplies will have to support big data analysis, i.e. for the detection of faulty apparatus due to undesired system parameter changes or failure detection.

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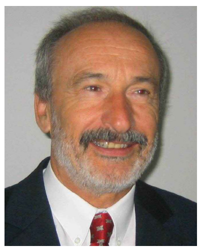

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