ELECTRON BEAM PHYSICAL VAPOR DEPOSITION (EB-PVD): APPLICATIONS ON FLEXIBLE MATERIALS AND POTENTIAL IN THE DEVELOPMENT OF TEXTILE THERMOELECTRIC GENERATORS

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ELECTRON BEAM PHYSICAL VAPOR DEPOSITION (EB-PVD): APPLICATIONS ON FLEXIBLE MATERIALS AND POTENTIAL IN THE DEVELOPMENT OF TEXTILE THERMOELECTRIC GENERATORS

ABSTRACT. Wearable electronics need on-body power sources for extended operation. Thermoelectric generators (TEGs) integrated into textiles are a promising solution, converting body heat into electricity to power wearable sensors and electronics. This approach reduces reliance on batteries and enables fully self-powered wearables. Current flexible TE materials are often conducting polymers or composites, which offer flexibility but have relatively low thermoelectric efficiency. Inorganic semiconductors (e.g., bismuth telluride Bi_2Te_3 and germanium telluride GeTe) provide far higher TE performance, but their rigidity and brittleness hinder direct incorporation into fabrics. Electron beam physical vapor deposition (EB-PVD) provides a way to deposit high-performance inorganic TE films onto flexible substrates. EB-PVD can coat fibers or polymer fabrics with ultrathin Bi_2Te_3 or GeTe layers, transferring the high Seebeck coefficients and conductivity of these inorganics onto a textile platform. However, mechanical and thermal mismatches between stiff films and soft fabrics can cause cracking or delamination under bending and temperature changes. This review summarizes recent advances in the use of EB-PVD for flexible thermoelectric textiles, highlighting both its advantages and current limitations as a deposition method for wearable applications.
KEYWORDS: EB-PVD, TEGs, flexible materials, nanomaterials, textiles

DEPUNERE FIZICĂ ÎN FAZĂ DE VAPORI CU FASCICUL DE ELECTRONI (EB-PVD): APLICAȚII ASUPRA MATERIALELOR FLEXIBILE ȘI POTENȚIAL ÎN DEZVOLTAREA GENERATOARELOR TERMOELECTRICE TEXTILE

REZUMAT. Electronicele purtabile necesită surse de alimentare pe corp pentru o funcționare extinsă. Generatoarele termoelectrice (TEG) integrate în textile reprezintă o soluție promițătoare, transformând căldura corpului în electricitate pentru a alimenta senzori și electronice purtabile. Această abordare reduce dependența de baterii și permite autoalimentarea completă a dispozitivelor purtabile. Materialele TE flexibile actuale sunt adesea polimeri sau compozite conductoare, care oferă flexibilitate, dar au o eficiență termoelectrică relativ scăzută. Semiconductorii anorganici (de exemplu, telurura de bismut Bi_2Te_3 și telurura de germaniu GeTe) oferă performanțe TE mult mai mari, însă rigiditatea și fragilitatea acestora împiedică încorporarea directă în țesături. Depunerea fizică în fază de vapori cu fascicul de electroni (EB-PVD) oferă o modalitate de a depune pelicule TE anorganice de înaltă performanță pe substraturi flexibile. EB-PVD poate acoperi fibrele sau țesăturile polimerice cu straturi ultrasubțiri de Bi_2Te_3 sau GeTe, transferând coeficienții Seebeck ridicați și conductivitatea acestor materiale anorganice pe o platformă textilă. Cu toate acestea, neconcordanțele mecanice și termice dintre peliculele rigide și țesăturile moi pot provoca fisuri sau delaminare la îndoire și la schimbări de temperatură. Această analiză rezumă progresele recente în utilizarea EB-PVD pentru textile termoelectrice flexibile, evidențiind atât avantajele, cât și limitele actuale ale acesteia ca metodă de depunere pentru aplicații purtabile.
CUVINTE CHEIE: EB-PVD, TEG-uri, materiale flexibile, nanomateriale, textile

L'ÉVAPORATION PAR FAISCEAU D'ÉLECTRONS (EB-PVD) : APPLICATIONS SUR LES MATÉRIAUX FLEXIBLES ET POTENTIEL DANS LE DÉVELOPPEMENT DE GÉNÉRATEURS THERMOÉLECTRIQUES TEXTILES

RESUME. Les appareils électroniques portables nécessitent des sources d'énergie intégrées au corps pour un fonctionnement prolongé. Les générateurs thermoélectriques (TEG) intégrés aux textiles constituent une solution prometteuse convertissant la chaleur corporelle en électricité pour alimenter les capteurs et les appareils électroniques portables. Cette approche réduit la dépendance aux batteries et permet de créer des appareils portables entièrement autonomes. Les matériaux thermoélectriques flexibles actuels sont souvent des polymères ou des composites conducteurs, qui offrent une certaine flexibilité, mais un rendement thermoélectrique relativement faible. Les semi-conducteurs inorganiques (par exemple, le tellurure de bismuth Bi_2Te_3 et le tellurure de germanium GeTe) offrent des performances thermoélectriques bien supérieures, mais leur rigidité et leur fragilité empêchent leur incorporation directe dans les tissus. Le dépôt physique en phase vapeur par faisceau d'électrons (EB-PVD) permet de déposer des films thermoélectriques inorganiques hautes performances sur des substrats flexibles. L'EB-PVD permet de revêtir des fibres ou des tissus polymères de couches ultrafines de Bi_2Te_3 ou de GeTe, transférant ainsi les coefficients Seebeck élevés et la conductivité de ces matériaux inorganiques à une plateforme textile. Cependant, les disparités mécaniques et thermiques entre les films rigides et les tissus souples peuvent provoquer des fissures ou un délaminage lors de la flexion et des variations de température. Cette revue résume les avancées récentes dans l'utilisation du dépôt EB-PVD pour les textiles thermoélectriques flexibles, soulignant ses avantages et ses limites actuelles comme méthode de dépôt pour les applications portables.
MOTS-CLES : EB-PVD, TEG, matériaux flexibles, nanomatériaux, textiles

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INTRODUCTION

Electron Beam Physical Vapor Deposition (EB-PVD) is a vacuum-based coating technology widely used for producing high-quality thin films. The process involves bombarding a target material with a focused electron beam generated by a heated filament in a vacuum chamber. The kinetic energy of the electrons is converted into heat upon impact with the target, causing local melting and evaporation of the material; the condensed vapors then deposit a thin layer onto substrates placed nearby. A schematic representation of the EB-PVD process is shown in Figure 1, illustrating the localized heating of the ingot and the direction of sublimated atom flow toward the substrate. However, ordinary textile fibers are dielectric materials and do not inherently attenuate electromagnetic fields. The necessary properties for EMI shielding—primarily high electrical conductivity and possibly magnetic permeability—must be imparted through various textile functionalization methods [2]. This can involve the integration of metallic yarns or fibers, coating fibers with thin metal or conductive polymer layers, impregnating with conductive or magnetic nanoparticles, or developing inherently conductive or magnetic fibers. Essentially, textiles become substrates for functional materials that enable them to reflect or absorb electromagnetic waves [3].

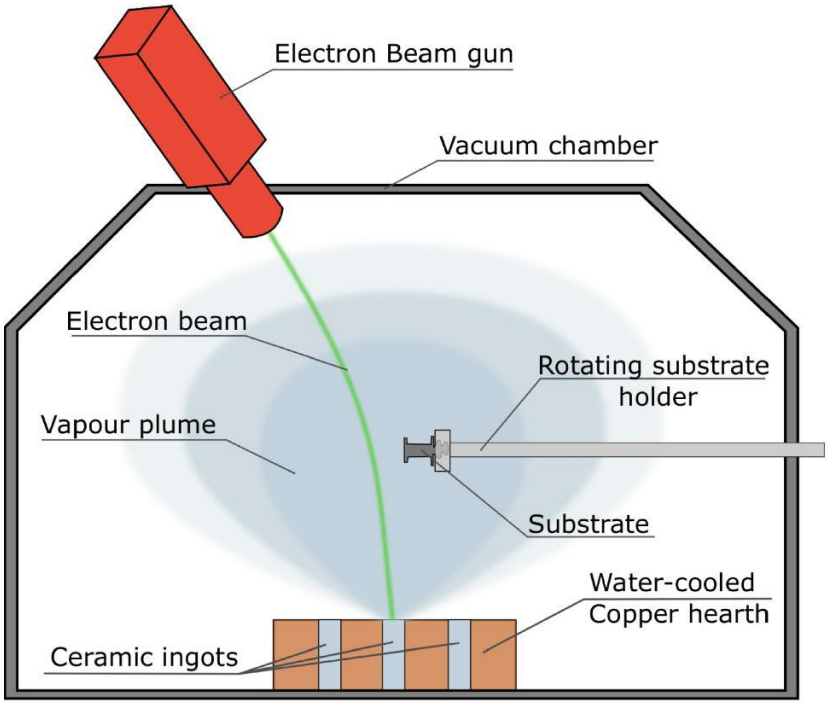

Figure 1. Illustrative diagram of the Electron Beam Physical Vapor Deposition (EB-PVD) process, highlighting the essential components of the setup: electron gun, vacuum chamber, ceramic ingots, rotating substrate holder, and the trajectory of the electron beam [2]

EB-PVD belongs to the category of Physical Vapor Deposition (PVD) processes, which are distinct from Chemical Vapor Deposition (CVD) methods in that they do not involve surface chemical reactions and can operate at lower temperatures [1]. Compared to other PVD techniques, EB-PVD stands out due to its high deposition rates and the high purity of the resulting films. For instance, EB-PVD can achieve deposition rates on the order of 0.1–100 µm/min (even up to ~150 µm/min in certain configurations) owing to the abundant evaporated flux. This allows for uniform coating of substrates, including those with complex geometries, particularly when the substrate is continuously rotated during deposition to ensure even exposure to the vapor stream [3].

Furthermore, the target material utilization efficiency is high, and the process has a reduced environmental impact (it does not produce liquid waste or toxic gases), thus making it a viable alternative to electroplating or other conventional coating techniques [3].

Thanks to these advantages, EB-PVD technology was initially developed and applied in demanding sectors such as the aerospace and energy industries. A notable example is the so-called *thermal barrier coatings* (TBCs) – ceramic thermal protection layers deposited on turbine blades of jet engines. TBCs based on yttria-stabilized zirconia (YSZ) are typically produced via EB-PVD, resulting in a columnar microstructure with oriented porosity that provides excellent resistance to thermal shock and heating/cooling cycles [3, 4]. This type of columnar coating, which cannot be achieved using other methods, exemplifies the EB-PVD process's ability to control microstructural architecture through the adjustment of parameters (substrate temperature, rotation speed, chamber pressure, etc.).

Additionally, EB-PVD enables the fabrication of multilayer structures and functionally graded compositions in a single processing step. For example, the composition of the deposited layer can be varied either continuously or stepwise by using multiple targets, thereby producing functionally graded layers or alternating metal/ceramic structures within the same deposition cycle [4]. This versatility has been demonstrated, for instance, in the fabrication of bicomponent thermal barrier coatings (a metallic bond coat of M–Cr–Al–Y and a ceramic YSZ layer) within the same evaporation batch, using a composite ingot designed to sequentially release the metallic and ceramic components [5].

In recent years, researchers have increasingly focused on extending EB-PVD applications beyond traditional domains, aiming at unconventional substrates such as flexible textile materials. Functional textiles represent an emerging direction in materials science, with applications in wearable electronics, embedded sensors in clothing, medical materials, flexible displays, and more. Typically, to impart special properties to textiles (electrical conductivity, antibacterial activity, hydrophobicity, thermal functionality, etc.), treatments such as nanoparticle impregnation, conductive polymer coatings, or vacuum-based methods like sputtering are employed [6]. However, EB-PVD offers the advantage of producing high-purity, adherent metallic or ceramic thin films without the use of chemical solutions or intermediate synthesis steps. Therefore, integrating EB-PVD into the field of textile materials could open new pathways for the development of smart textiles.

GENERAL PROCESS OF THE EB-PVD METHOD

The EB-PVD process takes place in a high vacuum chamber (typically between 7.5×10^{-5} Torr (10^{-2} Pa)) in which the source of the material to be deposited and the substrate to be coated are located. The material source is usually a crucible containing the solid target material (metals, alloys, or compounds in ingot form). An electron gun produces the high-energy electron beam required for evaporation: electrons are generated by thermionic emission from a heated tungsten filament and are accelerated towards the anode by a potential difference on the order of tens of kV. To focus and deflect the beam towards the target (which is not in a straight line with the filament, to avoid its contamination by vapors), a strong magnetic field is used to bend the trajectory of the electrons [1]. The electrons impact the surface of the target material in a concentrated area, generating an intense heating spot that can exceed temperatures of 2000–3000°C, sufficient to melt and locally vaporize the material almost instantly. A molten bath forms at the surface of the ingot, above which atoms and molecules detach in vapor form. These move ballistically in the rarefied environment and condense on the substrate and on the chamber walls that are in their range of action. Deposition takes place predominantly on surfaces directly exposed to the vapor flux, similar to other PVD processes.

Modern EB-PVD equipment allows fine control of several process parameters to obtain the desired structure of the deposited film: the electron beam power (current and voltage)

controls the evaporation rate; the substrate temperature influences atom mobility and, implicitly, the density and grain size of the layer; residual pressure and the nature of gases in the chamber can affect the microstructure; the rotation speed of the substrate and the device geometry (the incidence angle of vapors) can determine the appearance of inclined or dendritic columnar structures. In addition, some systems include auxiliary sources such as an ion beam directed at the substrate, either for preliminary cleaning of the substrate surface before deposition. All these variables make EB-PVD a complex process, capable of producing a variety of microstructures – from dense, smooth films to highly porous columnar structures – adapted to the target application [4].

An important aspect of the EB-PVD method is the versatility of the materials that can be used for deposition. Practically, any material that can be melted and evaporated in vacuum can serve as a target. Unlike sputtering, which requires electrically conductive targets and has lower yield for materials with high melting point, EB-PVD excels at evaporating refractory materials. Elements with low vapor pressure (e.g.: Mo, W, C) can be efficiently vaporized by the electron beam. Also, ceramic compounds (oxides, nitrides, carbides) can be deposited either by using directly dense ceramic targets (e.g. YSZ), or by evaporating the elemental components from separate crucibles followed by reaction on the substrate (e.g. co-deposition of titanium and aluminum in a reactive nitrogen atmosphere to form titanium-aluminum nitride). EB-PVD even allows the realization of alloys or doped layers by simultaneous evaporation from two or more sources with controlled rates. Many industrial EB-PVD systems are equipped with multiple targets that can be brought successively under the beam, allowing layered depositions or the realization of layers with gradually varying composition along the thickness axis (e.g. progressive transition from metallic to ceramic composition in a functionally graded thermal barrier) [2].

Therefore, EB-PVD can produce a wide range of advanced coatings: metallic (e.g. Cu, Ag, Au films for electronics or decorations), dielectric (SiO_2, Al_2O_3 for optics or insulating layers), superconducting (YBCO in cryogenic electronics), biomaterials (hydroxyapatite on medical implants), etc. The fact that the process takes place in high vacuum ensures the chemical purity of the films (minimal contamination with oxide or moisture) and excellent adhesion, due to the high energy of the condensed atoms and the possibility of ionic pre-cleaning of the substrate. On the other hand, EB-PVD involves expensive equipment and significant energy consumption (high voltage sources, vacuum pumps, cooling systems for targets and chamber walls, etc.). Also, the deposition is directional, which may hinder the uniform coating of substrates with complex geometry if substrate movement is not used. Nevertheless, technical advances have led to EB-PVD systems capable of roll-to-roll (R2R) processing of flexible films, making them optimal for high-volume applications such as those in the electronic textile industry. In the following sections we will see how these characteristics of EB-PVD have been exploited to obtain textile materials with functionalities [7].

APPLICATIONS OF THE EB-PVD METHOD ON FLEXIBLE TEXTILE MATERIALS METAL FIBERS AND YARNS INTEGRATION

An important direction in the field of smart textiles is the development of electro-conductive textiles, which can serve as sensors, heating elements, antennas, or interconnections for wearable electronic devices. Regular textile fibers (natural or synthetic) are electrically insulating, but can be made conductive by depositing a thin metallic layer on their surface. Common methods include chemical metallization (electroplating or electroless plating), coating with conductive inks (printing), or vacuum deposition via sputtering. EB-PVD has also proven effective for textile metallization, offering improved adhesion and uniform coverage. Visileanu *et al*. [6] reported in 2025 the production of conductive textile structures using an EB-PVD system, depositing copper and silver onto a cotton textile material. The fabric (100%

cotton, density 610 threads/10 cm) was prepared by washing and treating with bonding polymers (an acrylate and a urethane) to improve the continuity of the deposited metallic film. Without this treatment, the metal tended to penetrate between the fibers and failed to form a continuous film due to the roughness and porosity of the textile surface. After treatment, a thin conductive layer was achieved via EB-PVD, with a deposited metal mass of only ~5–7 μg/cm². Characterizations showed that the metallic film covered the fibers uniformly, providing the material with an electrical resistance on the order of ohms per square. Although both copper and silver were effective in imparting conductivity, silver proved more stable under washing and abrasion. The samples coated with Ag by EB-PVD retained a good part of their conductivity even after 5 washing cycles and 5000 abrasion cycles, according to the standard tests conducted by the authors (ISO 105-C06 and ISO 12947). This superior behavior is due both to the high adhesion of the film deposited by EB-PVD and the possible protective role of the polymer treatments applied to the fibers before metallization [6].

A major advantage of using EB-PVD for conductive coatings on textiles is the fineness and conformability of the deposited layer. Metallic films can be achieved with thicknesses of only tens to hundreds of nanometers, sufficient to ensure conductivity without significantly affecting the textile's flexibility, weight, or air permeability [6]. Practically, the coated fiber remains just as flexible, and the layer deforms along with the textile substrate due to its extreme thinness. This is a difference compared to wet methods (e.g., printing with silver paste), where the conductive layer usually has a greater thickness and can weigh down the material. Furthermore, EB-PVD takes place in a clean environment, free of contaminants, which translates to better long-term chemical stability of the films. The mentioned study also investigated and compared DC/RF magnetron sputtering depositions on the same textiles. It was found that both PVD methods provided similar initial conductivity properties, but the adhesion of the sputtered layers was slightly lower than that of those deposited by EB-PVD in the durability tests under washing. The sputtered films showed small delaminated areas after repeated cycles. This indicates that the higher energy of the atoms deposited by EB-PVD and the possibility of pre-activation of the textile surface (by mild heating or ion bombardment) ensure a closer contact between the film and the substrate [6].

Beyond copper and silver, EB-PVD can be used to evaporate and deposit a variety of conductive metals or alloys on textile materials, depending on the application. For example, for electromagnetic shielding screens, aluminum or nickel films can be deposited; for flexible electrical circuits, gold or copper-gold alloys may be used. A particular case of practical interest is antibacterial coatings on medical or hygienic textiles. Silver and copper ions are well known for their antimicrobial action, which is why these metals are often incorporated into textiles intended for medical equipment (gowns, bedding, bandages) or sports equipment. The PVD method allows the uniform application of a very thin layer of Ag or Cu on the surface of textile fibers, giving them long-lasting antibacterial properties [8, 9]. Scholz *et al*. investigated the antimicrobial properties of fabrics coated with precious metals (Ag, Au, Pt) by vacuum sputtering [10]. The metallized fabrics showed a significant reduction in bacterial load (including *Staphylococcus aureus*) compared to uncoated textiles, showing potential for applications in the medical field. Although that study used sputtering, it can be suggested that silver deposition via EB-PVD would have similar effects, considering the chemically inert nature of the process and the purity of the resulting layer. A nanometric layer of silver deposited on fibers can continuously release Ag ions under the action of moisture, preventing bacterial proliferation on the material's surface. Moreover, compared to chemical treatments (which may include the reduction of Ag compounds directly on the fiber, generating nanoparticles), the PVD method ensures stronger fixation of silver on the substrate, which translates to higher resistance to multiple washes. Thus, EB-PVD emerges as an

effective solution for producing durable antibacterial textiles, without resorting to potentially harmful or costly chemicals [10].

The application of the EB-PVD method to textile materials has proven feasible for obtaining conductive and functional textiles. The key to success lies in the proper preparation of the textile surface (cleaning, activation, or coating with a polymer primer) so that the fibers, which are flexible and porous, can support the formation of a continuous film. The literature results indicate that textiles metallized by EB-PVD can meet demanding performance requirements (conductivity, wear resistance, chemical stability), paving the way for their integration into wearable electronic devices. In the next section, we will explore an advanced application of these conductive textiles: textile thermogenerators, which convert heat directly into electrical energy.

EB-PVD APPLICATIONS IN THE DEVELOPMENT OF TEXTILE THERMOGENERATORS

Textile thermogenerators are flexible devices integrated into textile-like structures, designed to generate electrical energy by exploiting temperature differences, for example, between the human body and the ambient environment. They are based on the Seebeck thermoelectric effect: when there is a temperature gradient between the ends of a semiconductor element, an electric voltage is generated. By connecting multiple n-type and p-type thermoelectric elements in series, a generator capable of supplying direct current is created. Interest in wearable thermogenerators is high, as they can provide continuous power to body-worn sensors and electronic devices, eliminating dependence on conventional batteries. Unlike other portable energy sources (photovoltaics, which depend on sunlight, or kinetic generators, which require movement), thermogenerators can function passively by using body heat, offering a green and silent energy source as long as there is a temperature difference [7].

The challenge in creating textile thermogenerators lies in integrating thermoelectric (TE) materials—which are often fragile, inorganic, and require high processing temperatures—with flexible textile substrates, without compromising the TE performance or the wearability of the system. Numerous studies have addressed this issue through various strategies: incorporating thermoelectric fibers into the fabric (e.g., knitted binder fibers containing Bi_2Te_3 powders), depositing thermoelectric ink on textiles (by printing or dyeing with conductive organic compounds and TE nanoparticles), or laminating thin thermoelectric films onto textile supports. In this context, EB-PVD offers a promising approach, enabling the direct deposition of inorganic thermoelectric materials as thin films on flexible substrates, with precise control over thickness and composition [11, 12].

A demonstrative example of the potential of PVD in flexible thermogenerators is provided by Morgan *et al*. (2019), who fabricated thermoelectric generators on polymeric substrates using roll-to-roll compatible PVD techniques. In this study [7], the authors deposited a layered Bi_2Te_3/GeTe TEG system onto a thin polyimide ribbon via magnetron sputtering, achieving a thermoelectric leg-pair with a Seebeck coefficient of ~140 µV/K and a power output of ~0.4 nW per module at a temperature difference of 20 K. Additionally, they demonstrated a new high-productivity PVD instrument based on a pulsed electron beam, called Virtual Cathode Deposition (VCD), with which they rapidly deposited Bi_2Te_3/GeTe TEG films. The thermogenerator thus produced reached a Seebeck coefficient of ~250 µV/K per pair and ~0.2 nW per pair at a 20 K temperature difference. These results, although at the laboratory level, are encouraging—they show that PVD techniques (including electron beam-based ones) can produce functional thermoelectric devices on flexible substrates, with performances comparable to those obtained by classical methods on rigid substrates [7].

The direct application of EB-PVD in the fabrication of textile thermogenerators would involve the deposition of thermoelectric materials onto a textile support or onto intermediate layers applied to the textile. A practical possibility would be the use of a

thermostable textile material as a support, capable of being introduced into the EB-PVD chamber. Alternatively, textile fibers could be individually coated with TE material, then integrated into a woven or knitted structure. In either case, EB-PVD would offer the advantage of obtaining crystalline TE films with well-controlled composition [13]. EB-PVD deposition of thermoelectric materials has already been explored on rigid substrates to optimize microstructure. Smith *et al*. (2009) fabricated a thermoelectric microgenerator composed of thin Si/SiGe networks, sequentially deposited by EB-PVD on silicon, followed by high-energy Si ion irradiation. The ion bombardment reduced the thermal conductivity of the network and increased the Seebeck factor, leading to improved thermoelectric conversion efficiency. This example demonstrates that EB-PVD can produce advanced thermoelectric structures and that post-deposition treatments, such as doping or irradiation, can be applied to enhance performance [13].

To utilize these advantages in a textile thermogenerator, a few technical obstacles still need to be overcome. First, the thermal compatibility of the textile substrate with the process: many textile fibers (cotton, polyester) begin to degrade or decompose at temperatures above 200°C, and in EB-PVD, substrates can reach such temperatures either through thermal radiation from the target or intentionally, for film crystallization. Possible solutions include keeping the substrate at low temperature via active cooling of the substrate holder, or using high-temperature-resistant polymers (Kapton, PPS, PTFE, etc.). Second, the adhesion and mechanical stability of the thermoelectric layer on textile: TE materials such as Bi_2Te_3/GeTe TEG are brittle, and thin films can crack under repeated bending. Here, the typical microstructure of EB-PVD deposition may be paradoxically beneficial—a porous layer has better conformability under deformation and can accommodate stress through intercolumnar cracks without general delamination [14, 15]. Thus, an EB-PVD Bi_2Te_3/GeTe TEG film on a textile fiber could withstand repeated bending, unlike a dense film, which would continuously crack. Additionally, interposing a ductile buffer layer (e.g., a thin layer of Au or conductive polymer) between the fiber and the TE material could significantly improve the assembly's resilience.

Third, achieving sufficient generator output requires producing a large number of thermoelectric elements in series on an extended surface. EB-PVD could uniformly coat large textile surfaces, but the definition and connection of individual n/p elements require patterning. A suggested alternative in recent literature is the fabrication of individual n and p fibers (coaxially coated via PVD with different TE materials), which are then woven into a thermoelectric module-like structure. This modular strategy could be supported by EB-PVD by coating different types of yarns in a continuous configuration. Thus, a fully textile generator architecture can be achieved, where the coated yarns act as thermoelectric elements and electrical contacts can be realized by additional PVD metal layers applied to specific areas [16].

At the current stage [17], textile thermogenerators are still in the research phase, with several notable experimental demonstrations. For example, one group created a stretchable thermoelectric fabric using p- and n-type polymer nanocomposite yarns, achieving a power density of ~70 mW/m^2 at a temperature gradient of 44 K. Another group reported a 100% textile generator with printed organic elements, successfully generating several tens of microwatts from the body–environment temperature difference. Compared to these, the inorganic approach via EB-PVD could offer superior performance per element (as inorganic materials have significantly higher Seebeck coefficients and power factors than conductive organic materials). However, the flexibility and ease of fabrication of organic solutions is undeniable. Most likely, a convergence of the two directions will be necessary: for example, layering a nanostructured inorganic material onto textile via EB-PVD, then integrating it into a flexible polymer matrix for protection and reliability. Such a hybrid concept could combine the advantages of both worlds, enabling high-

efficiency textile thermogenerators that are also durable in real-world use [17].

Although no published reports currently exist on textile thermogenerators fully realized via EB-PVD, the fundamental elements of the technology indicate high potential for this application. EB-PVD can deposit established thermoelectric materials in unconventional forms and on non-standard substrates [17].

The remaining challenges—adhesion to fibers, thermal compatibility, and large-scale integration—can be addressed through process engineering (low-temperature deposition, use of buffer layers, and segmented deposition patterns). If these issues are resolved, EB-PVD could play a central role in the fabrication of the next generation of thermoactive textiles, capable of generating electricity from heat, increasing the autonomy of wearable electronic devices, and contributing to the realization of energy self-sustaining wearable systems. Electron beam physical vapor deposition (EB-PVD) offers key advantages over sputtering or chemical deposition methods for fabricating flexible thermoelectric generators on polymeric or textile substrates. It achieves significantly higher deposition rates and yields high-purity films with precise thickness control, while imparting minimal thermal load on the substrate. These features enable the growth of thicker, well-adhered thermoelectric coatings on heat-sensitive flexible substrates without degradation [18].

CONCLUSIONS

The Electron Beam Physical Vapor Deposition (EB-PVD) method has established itself as a process for obtaining high-performance thin films, already well-recognized in demanding industrial applications (thermal protection for turbines, optical layers, hard coatings, etc.). The present analysis highlighted the extension of this technology toward the field of flexible textile materials, a challenging area due to the delicate nature of the substrates. Recent studies demonstrate the feasibility of metallizing textiles by EB-PVD in order to confer functional properties – especially electrical conductivity and antibacterial activity. Cotton and other fiber textiles have been successfully coated with metals such as Cu or Ag, resulting in conductive textile materials that retain their flexibility and basic characteristics. It has been observed that substrate preparation (cleaning, smoothing, possible preliminary treatments with polymers) is essential for ensuring a continuous film on the surface of the fibers. Metallic films deposited by EB-PVD exhibit very good adhesion and uniformity, translating into increased durability of the properties (low resistivity maintained after mechanical stresses from washing/abrasion). Moreover, the use of metals with biocidal properties (Ag, Cu) opens the path to the realization of antibacterial or antifungal textiles without the need for complex chemical treatments – a simple nanometric layer deposited in vacuum can confer the material with persistent antibacterial activity.

With regard to textile thermogenerators, these represent an emerging application where EB-PVD could bring significant contributions. It has already been demonstrated that PVD processes are compatible with the fabrication of flexible thermoelectric generators on polymer films, including techniques derived from EB-PVD for the rapid deposition of active materials (Bi–Te, Sb–Te) [7]. The transposition of these technologies onto textile substrates could allow the direct integration of the energy generation function into clothing or accessories. EB-PVD offers the advantage of obtaining crystalline-discontinuous thermoelectric materials which may be more resistant to deformation cycles, as well as the possibility to precisely control dosage and composition (necessary for optimizing doping in TE materials). However, before the practical implementation of textile thermo-generators manufactured through EB-PVD, several aspects must be resolved: (i) maintaining the integrity of textile fibers under vacuum and energetic bombardment process conditions, (ii) ensuring stable electrical contacts between thermoelectric elements on flexible support, and (iii) large-scale production of such structures in a cost-effective manner.

Overall, EB-PVD is emerging as a promising technology for functionalizing textiles at the surface level with unmatched control of the properties of the added layer. Whether it is about creating a textile material that generates electricity from body heat, or a textile bandage with a metallic antibacterial surface, EB-PVD offers the necessary tools to realize such concepts at the laboratory level, with the perspective of transitioning to industrial production once vacuum roll-to-roll processing technologies mature. The scientific community has begun to demonstrate the feasibility of these ideas. It remains to be seen to what extent EB-PVD will be efficiently integrated into the manufacturing flow of the textile industry, known for high volumes and low costs. In conclusion, EB-PVD represents a bridge between the field of thin films and that of flexible materials, and the intelligent exploitation of its benefits could lead to a new generation of smart textiles with integrated electronic and energy functions [7, 17].

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