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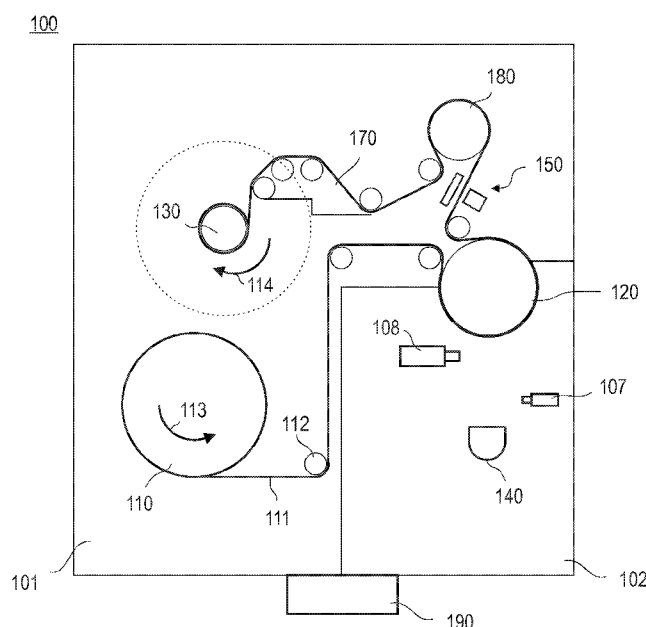


Fig. 1

(57) Abstract: Method and apparatus for producing an electrically insulating separator for use in electrochemical devices. The method includes providing a flexible substrate having a front side and a back side, and applying a porous coating comprising a ceramic material to at least one of the front side and back side of the flexible substrate, wherein applying the porous coating includes evaporating a metal in an inductively heated crucible.



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METHOD AND APPARATUS FOR THE PRODUCTION OF SEPARATORS FOR BATTERY APPLICATIONS

TECHNICAL FIELD

[0001] Embodiments of the present disclosure relate to a thin-film forming method and an apparatus for forming thin films on flexible substrates. Embodiments of the present disclosure particularly relate to a method of coating a separator and an apparatus for evaporating a metal-containing material and depositing a porous coating (e.g. AlO_x and/or SiO_x) including the evaporated metal-containing material on a separator for use in battery applications.

BACKGROUND

[0002] An electrical separator may, for instance, be described as a separator used in batteries and other arrangements in which electrodes have to be separated from each other while maintaining ion conductivity.

[0003] Conventionally, a separator includes a thin, porous, electrically insulating substance with high ion porosity, good mechanical strength and long-term stability with respect to the chemicals and solvents used in the system, for example, in the electrolyte of the battery. In batteries, the separator should completely electrically insulate the cathode from the anode. In addition, the separator should be permanently elastic and follow the movements in the system which stem not only from external loads but also from “breathing” of the electrodes as the ions are incorporated and discharged.

[0004] In general, the separator is crucial in determining the lifetime and the safety of the system in which it is used. For instance, the development of rechargeable batteries is being influenced to a significant degree by the development of suitable separator materials.

[0005] Battery systems, such as high-energy batteries or high-performance batteries are used in various applications in which it is important to have a maximum amount of electrical energy available. High-energy batteries or high-performance batteries are, for instance, used in applications including portable electronics, medical, transportation, grid-connected large energy storage, renewable energy storage, and uninterrupted power supply (UPS).

[0006] Generally, separators for use in high-energy batteries or high-performance batteries may be very thin in order to ensure a low specific space requirement and in order to minimize the internal resistance, have a high porosity in order to ensure low internal resistances, and are light in order to achieve a low specific weight of the battery system.

[0007] In many applications, large amounts of energy are required (for example in traction batteries for fully electric vehicles). The batteries in these applications are often based on reactive metals such as lithium or a lithium compound and, in the fully charged state, store a large amount of energy which should not be released in an uncontrolled manner. These battery applications have particular safety requirements and, in particular, the separators of such battery applications should comply to a very high standard in order to prevent malfunctions.

[0008] In view of the above, embodiments described herein aim to provide a method and apparatus for producing a safer separator for battery applications, especially, for high-energy batteries or high-performance batteries.

SUMMARY

[0009] According to an aspect of the present disclosure, a method for producing an electrically insulating separator for use in electrochemical devices is provided. The method comprises providing a flexible substrate having a front side and a back side, and applying a porous coating comprising a ceramic material to at least one of the front side and the back side of the flexible substrate, wherein applying the porous coating includes evaporating a metal in an inductively heated crucible.

[0010] Further, an evaporation apparatus for depositing a porous coating including a ceramic material on a surface of a flexible substrate is provided. The evaporation apparatus includes: an un-winding module for providing a roll of flexible substrate, a coating drum arranged for guiding the flexible substrate towards an evaporation chamber, a gas introduction device arranged for controllably introducing a reactive gas into the evaporation chamber, and a re-winding module for re-winding the flexible substrate, wherein the evaporation chamber includes at least one inductively heated crucible for evaporating a metal.

[0011] Further aspects, advantages and features of the present disclosure are apparent from the dependent claims, the description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the present disclosure, briefly summarized above, may be had by reference to typical embodiments. The accompanying drawings relate to embodiments of the present disclosure and are described in the following:

[0013] Fig. 1 shows a schematic view of an evaporation apparatus for depositing a porous coating including a ceramic material on a surface of a flexible substrate according to embodiments described herein;

[0014] Fig. 2 shows an enlarged section of the evaporation apparatus shown in Fig. 1; and

[0015] Fig. 3 schematically shows a method for producing an electrically insulating separator for use in electrochemical devices according to embodiments herein.

DETAILED DESCRIPTION OF EMBODIMENTS

[0016] Reference will now be made in detail to the various embodiments of the present disclosure, one or more examples of which are illustrated in the figures. Within the following description of the drawings, the same reference numbers refer to the same

components. Generally, only the differences with respect to individual embodiments are described. Each example is provided by way of explanation and is not meant as a limitation of the present disclosure. Features illustrated or described as part of one embodiment can be used on or in conjunction with other embodiments to yield yet a further embodiment. It is intended that the description includes such modifications and variations.

[0017] As used herein, the term “electrochemical device” may be understood to mean an electrochemical energy store which may be either rechargeable or non-rechargeable. In this respect, the present disclosure does not distinguish between the terms “accumulator” on the one hand, and “battery” on the other hand. In the context of the present disclosure, the terms “electrochemical device” and “electrochemical cell” are used synonymously hereinafter. An electrochemical cell, for instance, also covers a capacitor. In embodiments described herein, an electrochemical cell may be understood to be the minimum functioning unit of the energy store. In industrial practice, a multitude of electrochemical cells may be frequently connected in series or parallel in order to increase the total energy capacity of the store. In this context, reference is made to multiple electrochemical cells. An industrially designed battery may consequently have a single electrochemical cell or a multitude of electrochemical cells connected in parallel or in series.

[0018] In general, the electrochemical cell as an elementary functioning unit comprises two electrodes of opposing polarity, namely the negative anode and the positive cathode. The two electrodes are insulated from one another to prevent short circuits by the separator arranged between the electrodes. The cell is filled with an electrolyte—i.e. an ion conductor which is liquid, in gel form or occasionally solid. The separator is ion-pervious and permits exchange of ions between anode and cathode in the charge or discharge cycle.

[0019] For instance, in Li-ion electrochemical cells, the separator is often made from microporous polyethylene and polyolefin. During electrochemical reactions of charging and discharging cycles Li-ions are transported through the pores in the separator between the two electrodes of the electrochemical cell. High porosity may increase ionic conductivity. However, some high porosity separators may be susceptible to electrical shorts when, for instance, Li-dendrites formed during cycling create shorts between the electrodes. The composition and production of separators is very important in order to prevent malfunctions of the electrochemical cell.

[0020] According to embodiments herein, very thin separators may be produced. As a result, the proportion of the constituents of an electrochemical cell, which do not contribute to the activity of the electrochemical cell, can firstly be reduced. Secondly, the reduction in the thickness simultaneously brings about an increase in the ion conductivity. The separators according to embodiments herein permit an increased density in, for instance, a battery stack, so that a large amount of energy can be stored in the same volume. Generally, according to embodiments herein, the limiting current density can like-wise be increased, through enlargement of the electrode area.

[0021] The method of producing electrically insulating separators for use in electrochemical cells according to embodiments herein may be used for the production of separators that are separate from the electrochemical cell and also for the production of separators that are integrated directly into an electrochemical cell, such as, for instance, lithium-ion batteries having integrated separators. In integrated separator applications, a single-layer separator or a multi-layer separator may be formed directly on an electrode of the electrochemical cell.

[0022] In embodiments described herein, the separator may include a ceramic material, which is at least one electrically non-conductive or only very poorly conductive oxide of the metals aluminum, silicon, lead, zirconium, titanium, hafnium, lanthanum, magnesium, zinc, tin, cerium, yttrium, calcium, barium, strontium and combinations thereof. Despite silicon often being referred to as metalloid, in the context of the present disclosure silicon shall be included whenever reference is made to a metal. In general, according to embodiments herein, the separator may be optimized for electrochemical cells involving strongly alkaline electrolytes by choosing particularly alkali-resistant input materials. For instance, zirconium or titanium may be used instead of aluminum or silicon as an inorganic component to form the porous coating. The porous coating would then include zirconium oxide or titanium oxide instead of aluminum oxide or silicon oxide.

[0023] According to embodiments herein, the thickness of the porous coating deposited on the flexible substrate may be in the range from approx. 25 nm to approx. 300 nm, such as, for instance, from 100 nm to 200 nm. Separators with such a thickness allow for a very high energy density in an electrochemical cell. The evaporation apparatus according to embodiments herein, may allow for very high coating speeds as compared to conventional

separator coating techniques such as dip-coating. Generally, coating speeds may vary depending on the thickness and type of ceramic material to be deposited on the substrate.

[0024] According to embodiments herein, optionally the electrically insulating separators may include a polymer material selected from the group of: polyacrylonitrile, polyester, polyamide, polyimide, polyolefin, polytetrafluoroethylene, carboxymethyl cellulose, polyacrylic acid, polyethylene, polyethylene terephthalate, polyphenyl ether, polyvinyl chloride, polyvinylidene chloride, polyvinylidene fluoride, poly(vinylidene fluoride-co-hexafluoropropylene), polylactic acid, polypropylene, polybutylene, polybutylene terephthalate, polycarbonate, polytetrafluoroethylene, polystyrene, acrylonitrile butadiene styrene, poly(methyl methacrylate), polyoxymethylene, polysulfone, styrene-acrylonitrile, styrene-butadiene rubber, ethylene vinyl acetate, styrene maleic anhydride, and combinations thereof. Any other polymer materials that are stable in, for example, the strongly reducing conditions found in lithium based electrochemical cells may be used as well. According to embodiments herein, the separator can be optimized for electrochemical cells involving strongly alkaline electrolytes by choosing particularly alkali-resistant input materials. For instance, the separator may include a polyolefin or a polyacrylonitrile instead of polyester.

[0025] In embodiments described herein, the polymer material may have a high melting point, such as greater than 200°C. Separators including polymer materials with a high melting point are useful in electrochemical cells having a fast charging cycle. By virtue of the high thermal stability of a separator including a polymer material having a high melting point according to embodiments described herein, an electrochemical cell equipped with such a separator is not so thermally sensitive and is able to tolerate the temperature increase due to rapid charging without adverse changes to the separator or damage to the battery. These electrochemical cells may have a distinctly faster charging cycle, which may be useful in electric vehicles, which may be charged within a distinctively shorter periods of time.

[0026] According to embodiments herein, the separators of the present disclosure may have a porosity in the range from 10% to 90%, such as for instance in the range from 40% to 80%. The porous separator provides a pathway for electrolyte and reduces the electrolyte penetration time. Porosity as understood herein relates to the accessibility or the open pores. In general, the porosity can be determined via familiar methods to the skilled practitioner such as for instance by the method of mercury porosimetry or may be calculated

from the volume and the density of the materials used on the assumption that all the pores are open pores.

[0027] Fig. 1 shows a schematic view of an evaporation apparatus 100 for depositing a porous coating including a ceramic material on a surface of a flexible substrate 111. The evaporation apparatus 100 includes a loading/unloading chamber 101 for loading/unloading a flexible substrate 111 into and from the evaporation apparatus 100. According to embodiments herein, the loading/unloading chamber may be held under vacuum during processing of the flexible substrate. A vacuum device 190, such as a vacuum pump is provided to evacuate the loading/unloading chamber 101.

[0028] According to embodiments herein, the loading/unloading chamber 101 includes an un-winding module 110 and a re-winding module 130. An unwind roll of flexible substrate 111 may be provided at the un-winding module 110. During processing, the flexible substrate 111 may be un-wound (arrow 113) and guided by one or more guide rolls 112 to a coating drum 120. After being processed, the flexible substrate may be wound (arrow 114) on a re-wind roll in the re-winding module 130.

[0029] Optionally, according to embodiments herein, the loading/unloading chamber 101 may include a tension module 180, for instance, including one or more tension rollers. In embodiments herein, the loading/unloading chamber 101 may also include a pivot device 170, such as, for instance, a pivot arm. The pivot device 170 is configured to be moveable with respect to the re-winding module 130.

[0030] In embodiments herein, the evaporation apparatus 100 includes an evaporation chamber 102, in which a metal may be evaporated. The evaporation chamber may be evacuated by the same vacuum device 190 used to evacuate the loading/unloading chamber 101. According to further embodiments described herein, the evaporation chamber may also have a vacuum device that is separate from the vacuum device of the loading/unloading chamber.

[0031] The evaporation apparatus shown in Fig. 1 further includes an evaporation device 140 with which a metal may be evaporated. According to embodiments herein, the evaporation device may be one or more inductively heated crucibles. The inductively heated crucible may, for instance, be configured for evaporating a metal in a vacuum environment by

RF induction-heating, in particular by MF induction-heating. In further embodiments herein, the metal may be provided in crucibles that are exchangeable, such as, for example in one or more graphite vessels. Generally, according to embodiments herein, the exchangeable crucible may include an insulating material that surrounds the crucible. One or more induction coils may be wrapped around the crucible and the insulating material. According to embodiments herein, the one or more inductive coils may be water cooled. Where exchangeable crucibles are used, no wire needs to be fed into the evaporation apparatus. The exchangeable crucibles may be pre-loaded with a metal and may be replaced or refilled periodically. Generally, providing the metal in batches has the advantage of accurately controlling the amount of metal being evaporated.

[0032] In contrast to conventional evaporation methods that use resistance heating of crucibles to evaporate metals, using an inductively heated crucible allows for the heating process to be generated inside of the crucible itself, instead of by an external source via heat conduction. The inductively heated crucible has the advantage that all the walls of the crucible are heated very rapidly and evenly. The evaporation temperature of the metal may be controlled more closely than with conventional resistance heated crucibles. According to embodiments of the present disclosure, when using an inductively heated crucible it is unnecessary to heat the crucible above the evaporation temperature of the metal, which allows for a more controlled and efficient evaporation of the metal in order for the porous coating deposited on a flexible substrate to be more homogenous. Close control of the temperature of the crucible also prevents/reduces pinholes and through-hole defects in the porous coating on the substrate by diminishing the likelihood of splashing of the evaporating metal. Pinhole and through-hole defects in separators may cause shorts in electrochemical cells.

[0033] According to embodiments herein, the inductively heated crucible may, for instance, be surrounded by one or more induction coils. The induction coils may be an integral part of the inductively heated crucible according to embodiments herein. In yet further embodiments herein, the induction coils and the inductively heated crucible may be provided as separate parts. Providing the inductively heated crucible and the induction coils separately allows for easy maintenance of the evaporation apparatus.

[0034] In embodiments described herein, the evaporation apparatus may include a power source 240 (shown in Fig. 2). The power source may be connected to the induction coils. Generally, according to embodiments herein, the power source is an AC power source

that is configured to provide electricity with a low voltage but high current and high frequency. The reaction power may be increased, for instance, by including a resonant circuit. According to embodiments herein, in addition or alternatively to electrically conductive materials, the inductively heated crucible may, for instance, include ferromagnetic materials. Magnetic materials may, for instance, improve the induction heat process and may allow for a better control of the evaporation temperature of metal.

[0035] According to embodiments described herein, the coating drum 120 of the evaporation apparatus 100 may separate the loading/unloading chamber 101 from the evaporation chamber 102. The coating drum 120 is configured to guide the flexible substrate 111 into the evaporation chamber 102. Generally, the coating drum is arranged in the evaporation apparatus so that the flexible substrate passes over the evaporation device. In embodiments herein, the coating drum may be cooled.

[0036] The evaporation chamber 102 according to embodiments herein may include a plasma source 108 configured to produce a plasma between the evaporation device 140 and the coating drum 120. The plasma source may, for instance, be an electron beam device configured to ignite a plasma with an electron beam. According to further embodiments herein, the plasma source may be a hollow anode deposition plasma source. The plasma may help to prevent/reduce pinholes and through-hole defects in the porous coating on the substrate by further diminishing the likelihood of splashing of the evaporating metal. The plasma may also further excite the particles of the evaporated metal. According to embodiments herein, the plasma may increase the density and uniformity of the porous coating deposited on the flexible substrate.

[0037] The evaporation apparatus 100 of Fig. 1, further includes a gas introduction device 107 arranged for controllably introducing a reactive gas into the evaporation chamber 102. The gas introduction device may, for instance, include a nozzle and supply tube connected to, for example, an oxygen supply for providing oxygen into the evaporation chamber 102.

[0038] According to embodiments herein, the oxygen gas may, for example, react with the evaporated metal to form a ceramic coating on the flexible substrate. For instance, separators according to embodiments herein for use in electrochemical cells may include at least one of AlO_x and SiO_x . The metal such as aluminum and/or silicon may be evaporated by

the inductively heated crucible and oxygen may be supplied to the evaporated metal via the gas introduction device. According to embodiments herein, in order to attain a separator having a large proportion of at least one of stoichiometric Al_2O_3 and stoichiometric SiO_2 , the evaporation rate of the metal, amount of oxygen gas, pressure within the evaporation chamber and plasma density may be adjusted accordingly.

[0039] According to embodiments herein, the evaporation apparatus may include an inline monitoring system 150 adapted to acquire a monitoring signal including information on the uniformity and composition of the porous coating deposited on the flexible substrate. In embodiments described herein, the inline monitoring system may, for instance, include an optical measurement device. For porous AlO_x and SiO_x coatings, the optical measurement device may, for instance, be configured to operate at a wavelength of approx. 370 nm. The detection sensitivity of the optical measurement device may be adapted depending on the type of porous coating applied to the flexible substrate.

[0040] Fig. 2 shows an enlarged section 200 of the evaporation apparatus 100 shown in Fig. 1. According to embodiments herein, the evaporation apparatus 100 may include a control system 220. The control system 220 may be connected to one or more of the inline monitoring systems 150, the gas introduction device 107, the plasma source 108 and the power source 240. According to embodiments herein, the control system is configured to adjust at least one of a power provided to the evaporation device, a power provided to the plasma source, an amount of reactive gas and an orientation of a gas flow of the reactive gas introduced into the evaporation chamber by the gas introduction device in response to the monitoring signal of the inline monitoring device.

[0041] In embodiments herein, the gas introduction device 107 may be arranged to provide a gas flow of the reactive gas in a direction approx. parallel to an evaporation direction 230 of the metal. According to embodiments herein, the orientation of the gas flow provided by the gas introduction device may be adjusted in dependence of at least one of the uniformity and composition of the porous coating. Providing the flow of reactive gas parallel to the evaporation direction of the metal may ensure a more efficient reaction between the reactive gas and the evaporated metal to form the porous coating 211 on the flexible substrate 111. Arranging the gas introduction device 107 to introduce a reactive gas in a direction essentially parallel to the evaporation direction 230 of the metal from the

evaporation device 140 may also help to better control the coating process by being able to more accurately control the amount of reactive gas, which interacts with the evaporated metal.

[0042] According to embodiments herein, the plasma 210 may be guided in a direction essentially perpendicular to the evaporation direction 230 of the metal. Guiding the plasma in a direction approx. parallel to the evaporation direction of the metal may further help to prevent any splashing of the evaporating metal and may reduce the pinhole defects of the porous coating on the flexible substrate.

[0043] Fig. 3 schematically shows a method 300 for producing an electrically insulating separator for use in electrochemical devices according to embodiments herein. The method 300 includes providing 310 a flexible substrate having a front side and a back side. According to embodiments herein, providing a flexible substrate may include guiding the flexible substrate from an un-winding module to a re-winding module via a coating drum of an evaporation apparatus.

[0044] In embodiments described herein, the method may further include evaporating 320 a metal in an inductively heated crucible. Generally, according to embodiments herein, aluminum and/or silicon may be evaporated by an inductively heated crucible. In embodiments herein, the method further includes applying 330 a porous layer including a ceramic material to at least one of the front side and back side of the flexible substrate.

[0045] Generally, according to embodiments herein the evaporated metal may react with a reactive gas to form the porous coating on the flexible substrate. In embodiments herein, the metal may be evaporated in a vacuum environment. For example, evaporated aluminum may react with oxygen to form a porous AlO_x layer on the flexible substrate.

[0046] According to embodiments herein, evaporating the metal in the inductively heated crucible may further include sensing 340 an evaporation temperature at which the metal evaporates and adjusting a power provided to evaporate the metal in the inductively heated crucible in dependence of the sensed evaporation temperature. Monitoring and adjusting the evaporation temperature may improve the energy efficiency of the method for producing an electrically insulating separator and may help to prevent any pinhole defects of the porous coating applied to the flexible substrate.

[0047] In embodiments described herein, the porous coating applied to the flexible substrate may have a thickness from approx. 25 nm to approx. 300 nm, such as, for instance, from 100 nm to 200 nm.

[0048] According to embodiments herein, evaporating the metal in the inductively heated crucible may further include providing 350 a reactive gas such as, for example, oxygen to the evaporated metal. In embodiments herein, the reactive gas may be provided in a direction essentially parallel to the evaporation direction of the metal.

[0049] The method for producing an electrically insulating separator may further include providing 360 a plasma between the evaporated metal and the flexible substrate. The plasma may increase the density of the porous coating on the flexible substrate and may also help to reduce pinhole defects of the porous coating. Generally, according to embodiments herein the plasma may be provided by, for instance, an electron beam device or a hollow anode deposition plasma source. The density of the porous coating may be influenced by the density of the plasma.

[0050] According to embodiments herein, the method for producing an electrically insulating separator may further include monitoring 370 one or more of the uniformity and composition of the porous coating deposited on the flexible substrate. Further, monitoring the uniformity and composition of the porous coating may include detecting pinhole and through-hole defects in the porous coating. Generally, according to embodiments herein monitoring at least one of the uniformity and composition of the porous coating may further include adjusting at least one of the power provided to evaporate the metal, the power provided to the plasma, the amount of reactive gas and orientation of a gas flow of the reactive gas provided to the evaporated metal, and the speed at which the flexible substrate is guided, for instance, from an un-winding module to a re-winding module of an evaporation apparatus.

[0051] According to embodiments herein, the stoichiometry of the deposited porous layer on the flexible substrate may, for instance, be influenced by the evaporation rate of the metal and the amount of reactive gas provided to the evaporated metal. Further aspects that may influence the stoichiometry of the deposited porous layer may be the pressure differential between the vacuum inside of the evaporation chamber and the pressure of the surrounding atmosphere. For instance, if the porous coating includes too much non-

stoichiometric AlO_x and/or non-stoichiometric SiO_x , the amount of oxygen may be changed to increase the amount of stoichiometric Al_2O_3 and/or SiO_2 in the porous coating.

[0052] This written description uses examples to disclose the disclosure, including the best mode, and also to enable any person skilled in the art to practice the described subject-matter, including making and using any apparatus or system and performing any incorporated methods. Embodiments described herein provide an improved method and apparatus for producing a separator having a high porosity for good ionic conductivity, complex pore structure with no/reduced pinhole or through-hole defects to suppress shorts, excellent thermal and mechanical stability and can be produced at low cost. While various specific embodiments have been disclosed in the foregoing, mutually non-exclusive features of the embodiments described above may be combined with each other. The patentable scope is defined by the claims, and other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

CLAIMS

1. A method for producing an electrically insulating separator for use in electrochemical devices, the method comprising:
 - providing a flexible substrate having a front side and a back side, and
 - applying a porous coating comprising a ceramic material to at least one of the front side and the back side of the flexible substrate,
 - wherein applying the porous coating includes evaporating a metal in an inductively heated crucible.
2. The method according to claim 1, wherein the evaporating the metal in the inductively heated crucible further includes sensing an evaporation temperature at which the metal evaporates and adjusting a power provided to evaporate the metal in the inductively heated crucible in dependence of the sensed evaporation temperature.
3. The method according to claim 1 or 2, wherein the applied porous coating has a thickness from approx. 25 nm to approx. 300 nm.
4. The method according to any of claims 1 to 3, wherein the evaporating the metal in the inductively heated crucible further includes providing a reactive gas to the evaporated metal.
5. The method according to claim 4, further comprising adjusting at least one of the amount of reactive gas provided to the evaporated metal and the orientation of a gas flow of the reactive gas provided to the evaporated metal dependent on at least one of the uniformity and composition of the porous coating.
6. The method according to claim 4 or 5, wherein the reactive gas comprises oxygen.
7. The method according to any of claims 1 to 6, wherein the metal comprises an element selected from the group including: aluminum, silicon, lead, zirconium, titanium, hafnium, lanthanum, magnesium, zinc, tin, cerium, yttrium, calcium, barium, strontium and combinations thereof.

8. The method according to any of claims 1 to 7, further comprising providing a plasma between the evaporated metal and the flexible substrate.
9. The method according to claim 8, wherein the plasma is provided with an electron beam device or a hollow anode deposition plasma source.
10. The method according to claim 8 or 9, wherein a power provided to the plasma is adjusted dependent on at least one of the uniformity and composition of the porous coating.
11. An evaporation apparatus for depositing a porous coating comprising a ceramic material on a surface of a flexible substrate, the evaporation apparatus comprising:
 - an evaporation chamber;
 - an un-winding module for providing a roll of the flexible substrate;
 - a coating drum arranged for guiding the flexible substrate towards the evaporation chamber of the evaporation apparatus;
 - a gas introduction device arranged for controllably introducing a reactive gas into the evaporation chamber, and
 - a re-winding module for re-winding the flexible substrate, wherein the evaporation chamber includes at least one inductively heated crucible for evaporating a metal.
12. The evaporation apparatus according to claim 11, further including a plasma source configured to provide a plasma between the inductively heated crucible and the coating drum.
13. The evaporation apparatus according to claim 12, wherein the plasma source is an electron beam device or a hollow anode deposition plasma source.
14. The evaporation apparatus according to any of claims 11 to 13, further including an inline monitoring system adapted to produce a monitoring signal comprising information on one or more of the uniformity and composition of the porous coating deposited on the flexible substrate.
15. The evaporation apparatus according to claim 14, further including a control system configured to adjust at least one of a power provided to the inductively heated crucible, the

power provided to the plasma source, the amount of reactive gas, and the orientation of a gas flow of the reactive gas introduced into the evaporation chamber by the gas introduction device in response to the monitoring signal of the inline monitoring device.

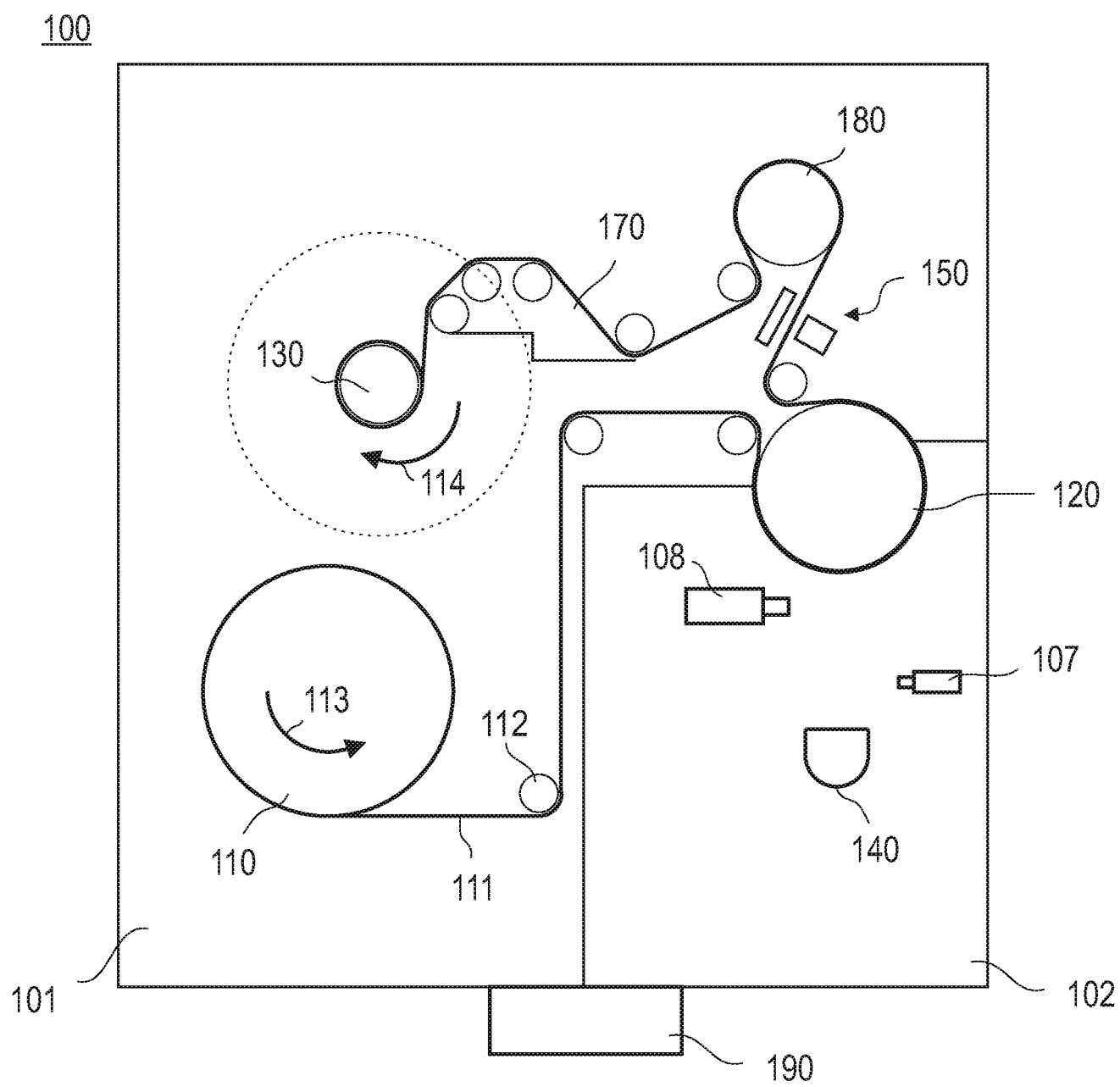
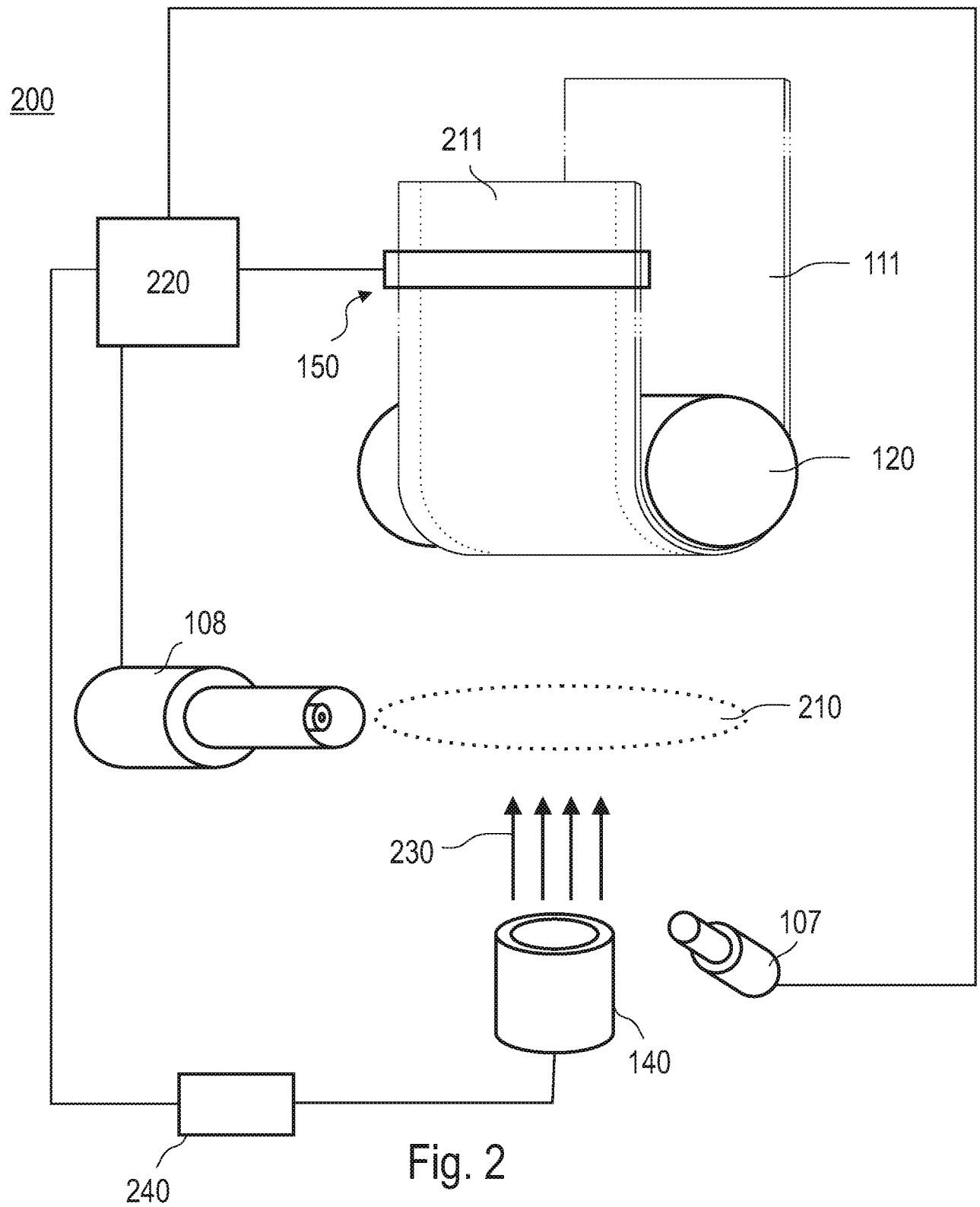


Fig. 1



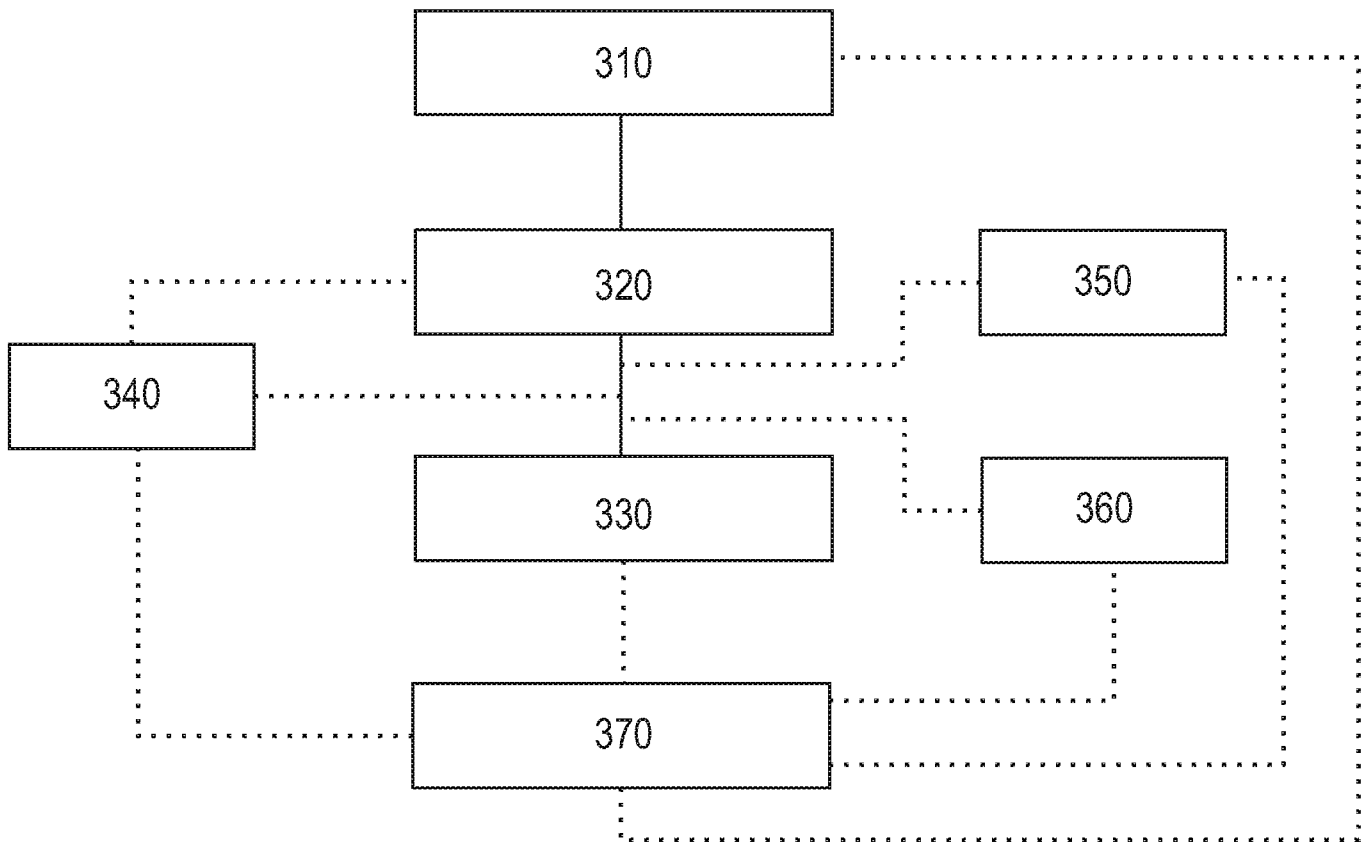
300

Fig. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/029224

A. CLASSIFICATION OF SUBJECT MATTER		
INV.	C23C14/00 H01M2/16	C23C14/08 H01M10/24
	C23C14/56	C23C14/26
		H01M2/14
ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) C23C H01M		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	paragraph [0018]; figure 1 paragraph [0021]; figure 1 paragraph [0023]; figure 1 paragraph [0024]; figure 1 paragraphs [0001], [0012] paragraphs [0025], [0026], [0028]	13-15
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Date of the actual completion of the international search 25 January 2017		Date of mailing of the international search report 02/02/2017
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Kudelka, Stephan

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