[0005] Breakdown of the dielectric layer usually occurs because intensity of an electric field becomes high enough to free electrons from atoms of the dielectric material and make them conduct an electric current from one electrode to another. Presence of impurities in the dielectric or imperfections (electric defects) of the crystal structure can result in an avalanche breakdown as observed in semiconductor devices. Thus, electrically conductive channels are formed in the dielectric layer when breakdown occurs. These channels have exit points on both surfaces of the dielectric layer.

[0006] Capacitors as energy storage device have well-known advantages versus electrochemical energy storage, e.g. a battery. Compared to batteries, capacitors are able to store energy with very high power density, i.e. charge/recharge rates, have long shelf life with little degradation, and can be charged and discharged (cycled) hundreds of thousands or millions of times. However, capacitors often do not store energy in small volume or weight as in case of a battery, or at low energy storage cost, which makes capacitors impractical for some applications, for example electric vehicles.

SUMMARY

[0007] The present disclosure provides self-healing capacitor and methods of production thereof. A self-healing capacitor of the present disclosure can solve a problem of increase of volumetric and mass density of reserved energy associated with some energy storage devices, and at the same time reduce cost of materials and manufacturing process.

[0007a] In an aspect, a self-healing capacitor comprises a first electrode, a second electrode, and a dielectric layer disposed between said first and second electrodes and having first surface facing the first electrode and a second surface facing the second electrode. At least one of the electrodes comprises a metal foam, wherein the metal foam is configured to form contact breaker by way of metal evaporation at an end of a conductive channel in the dielectric layer when current flows in the conductive channel as a result of application of a voltage between the first electrode and second electrode.

[0007b] In an aspect, a method of producing a self-healing capacitor, comprising: (a) applying an electric voltage across a first electrode and a second electrode that are separated by a dielectric layer, which applying comprises a gradual enhancement of the electric voltage to achieve electric breakdown, wherein at least one of the first and second electrodes includes a metal foam; (b) applying an electric field across the first electrode and the second electrode to form electrically conductive channels with exit points on opposing surfaces of the dielectric layer; (c) applying a current through the first and second electrodes to (i) induce Joule heating in at least one of the first and second electrodes and (ii) form local contact breakers in at least one of the first and second electrodes, which local contact

breakers are formed adjacent or in proximity to the exit points; and (d) terminating the application of the current upon formation of the local contact breakers.

[0008] In an embodiment, a self-healing capacitor comprises a first electrode, a second electrode, and a dielectric layer disposed between said first and second electrodes and having first surface facing the first electrode and second surface facing the second electrode. At least one of the electrodes comprises metal foam. Said dielectric layer has a plurality of electrically conductive channels each of them having one exit point located on the first surface of the dielectric layer and another exit point located on the second surface of the dielectric layer. Each of said first and second electrodes comprises at least one local contact breaker adjacent to the dielectric layer and located opposite to at least one exit point that interferes with passage of electric current through the conductive channels in the dielectric layer. The electrodes are planar and can be nearly or substantially parallel to each other, though not necessarily flat. The electrodes can be off-set from a parallel configuration.

[0009] In another embodiment, a method of producing a self-healing capacitor having at least one electrode made of metal foam, which comprises a) application of an electric voltage to capacitor electrodes and gradual enhancement of the magnitude of the voltage until electric breakdown of a dielectric layer will occur, b) formation under influence of electric field of electrically conductive channels which have exit

CLAIMS

WHAT IS CLAIMED IS:

1. A self-healing capacitor comprising

a first electrode,

a second electrode, and

a dielectric layer disposed between said first and second electrodes and having first surface facing the first electrode and a second surface facing the second electrode,

wherein at least one of the electrodes comprises a metal foam, wherein the metal foam is configured to form contact breaker by way of metal evaporation at an end of a conductive channel in the dielectric layer when current flows in the conductive channel as a result of application of a voltage between the first electrode and second electrode.

2. A self-healing capacitor according to claim 1, wherein said dielectric layer comprises a plurality of electrically conductive channels, each of said channels having one exit point located on the first surface of the dielectric layer and another exit point located on the second surface of the dielectric layer, and

wherein each of said first and second electrodes comprises at least one local contact breaker adjacent to the dielectric layer and located opposite to at least one exit point that interferes with passage of electric current through the conductive channels in the dielectric layer.

3. A self-healing capacitor according to claim 2, wherein the at least one local contact breaker is a hole that penetrates an entire thickness of a respective one of the first and second electrodes.

4. A self-healing capacitor according to claim 2, wherein the at least one local contact breaker is a dome structure.

5. A self-healing capacitor according to claim 2, wherein the electrically conductive channel includes electric defects united together due to breakdown of the dielectric layer.

6. A self-healing capacitor according to claim 1, wherein the metal foam includes Aluminum (Al).

7. A self-healing capacitor according to claim 1, wherein the metal foam includes Nickel (Ni).

8. A self-healing capacitor according to claim 1, wherein the metal foam includes Iron (Fe).

9. A self-healing capacitor according to claim 1, wherein the metal foam includes Copper (Cu).

10. A self-healing capacitor according to claim 1, wherein a melting temperature of the metal foam is from about 400°C. to about 700°C.

11. A self-healing capacitor according to claim 1, wherein a metal content in the metal foam is from about 5% to about 30% by weight.

12. A self-healing capacitor according to claim 1, wherein the metal foam is of a closed bubble type.

13. A self-healing capacitor according to claim 1, wherein the first electrode comprises the metal foam and the second electrode comprises a foil.

14. A self-healing capacitor according to claim 13, wherein the foil includes Aluminum (Al).

15. A self-healing capacitor according to claim 13, wherein the foil includes Nickel (Ni).

16. A self-healing capacitor according to claim 13, wherein the foil includes Iron (Fe).

17. A self-healing capacitor according to claim 13, wherein the foil includes Copper (Cu).

18. A self-healing capacitor according to claim 1, wherein the first electrode comprises the metal foam and the second electrode comprises a deposited thin film metal.

19. A self-healing capacitor according to claim 18, wherein the deposited thin film metal includes Aluminum (Al).

20. A self-healing capacitor according to claim 18, wherein the deposited thin film metal includes Nickel (Ni).

21. A self-healing capacitor according to claim 18, wherein the deposited thin film metal includes Fe.

22. A self-healing capacitor according to claim 18, wherein the deposited thin film metal includes Cu.

23. A self-healing capacitor according to claim 1, wherein the resistivity of the metal foam is tuned such that the metal foam ablates before the dielectric layer when current flows in a conductive channel through the dielectric layer as a result of application of a voltage between the first electrode and second electrode.

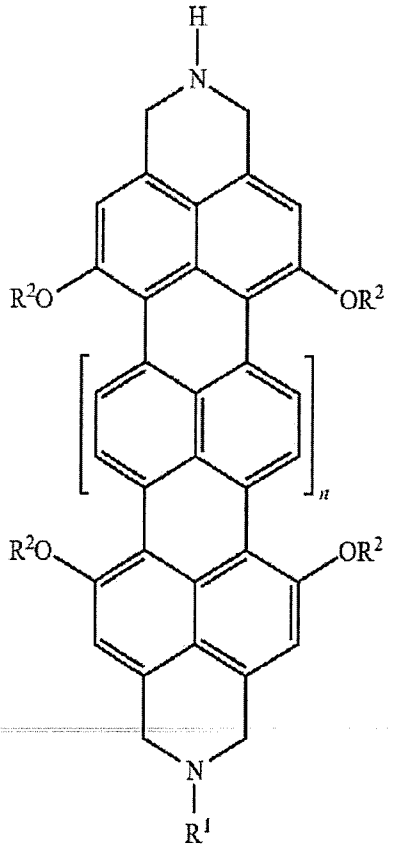
24. A self-healing capacitor according to claim 1, wherein the dielectric layer comprises modified organic compounds of the general structural formula I:

$$\{Cor\}(M)_n, \qquad (I)$$

wherein Cor is a polycyclic organic compound with conjugated π-system, each M is a modifying functional group; and n is a number of the modifying functional groups that is greater than or equal to zero.

25. A self-healing capacitor according to claim 24 wherein the modifying functional groups are selected from the group consisting of alkyl, aryl, substituted alkyl, and substituted aryl.

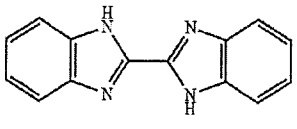
26. A self-healing capacitor according to claim 24, wherein the polycyclic organic compound includes a material with the following structure:



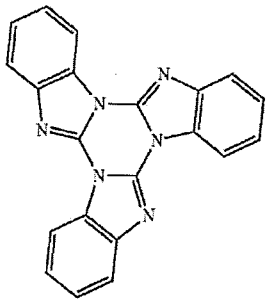
wherein n is a number ranging from 1-6, R^1 is diisopropylphenil, and R^2 is tert-octyphenil.

27. A self-healing capacitor according to claim 24, wherein the polycyclic organic compound is selected from the group consisting of oligophenyl, imidazole, pyrazole, acenaphthene, triaizine, indanthrone and structures 1-41:

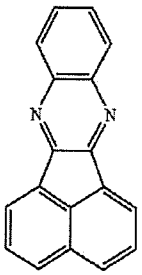
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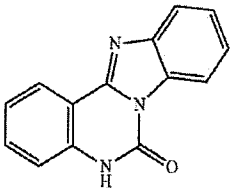
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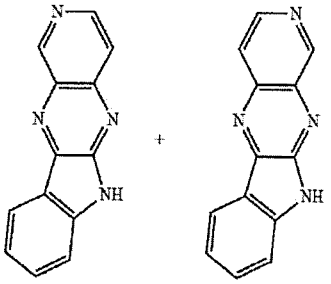
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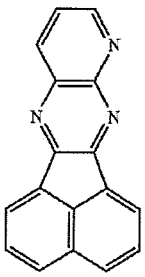
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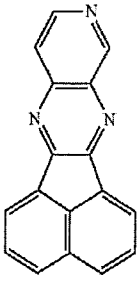
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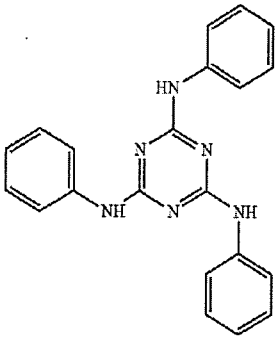
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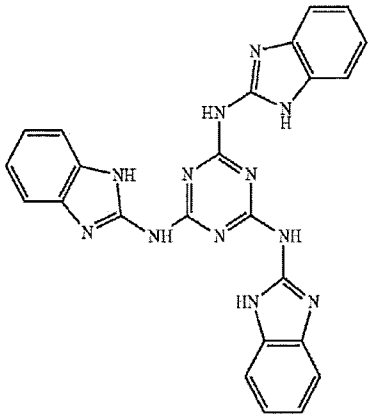
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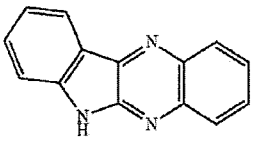
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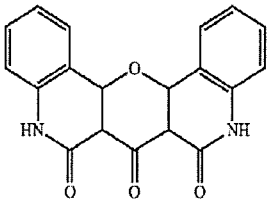
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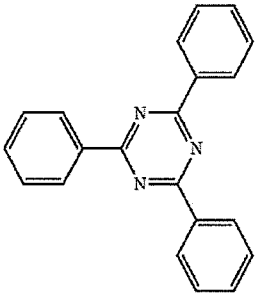
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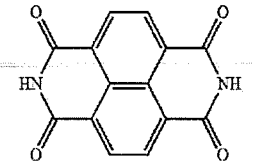
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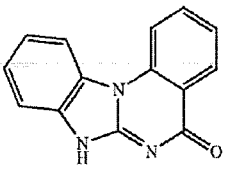
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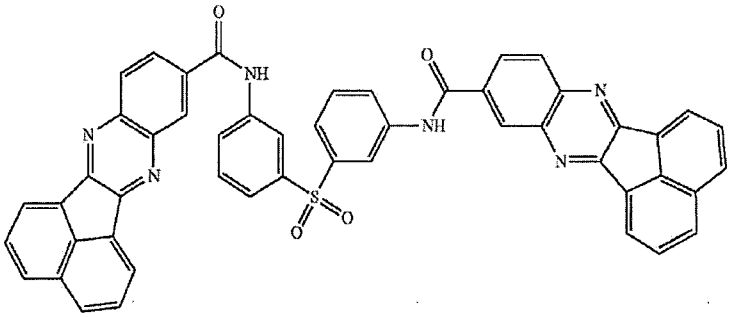
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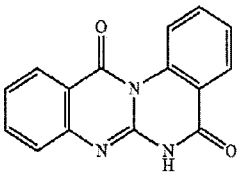
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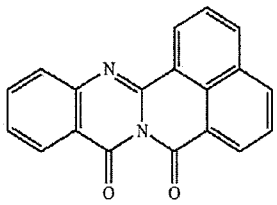
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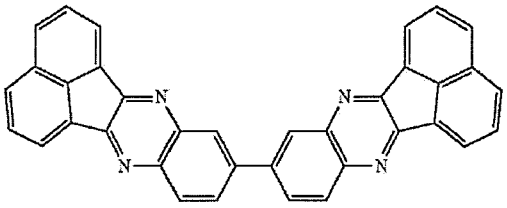
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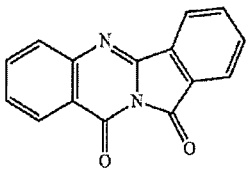
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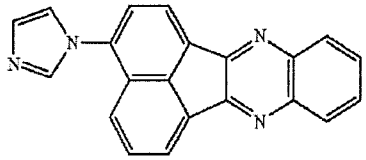
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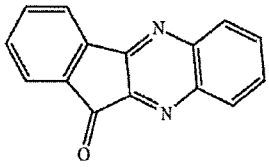
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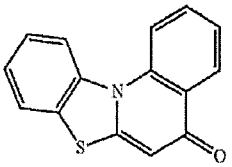
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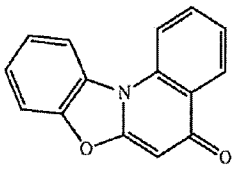
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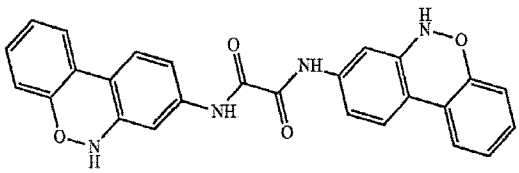
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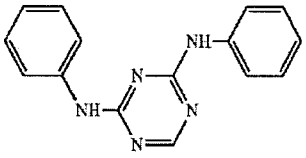
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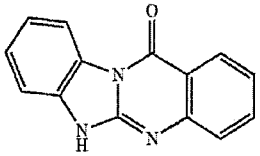
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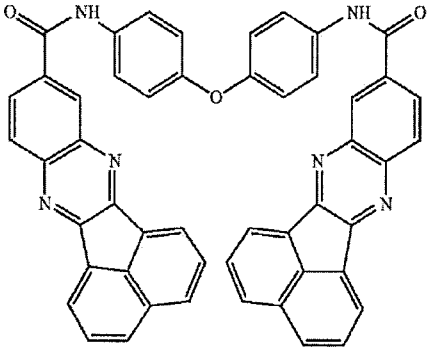
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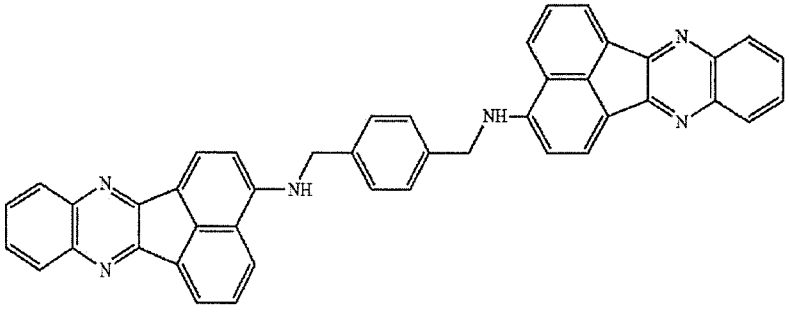
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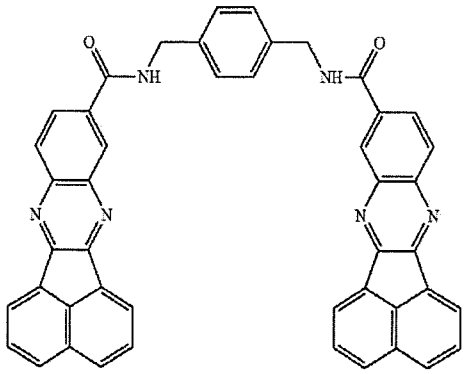
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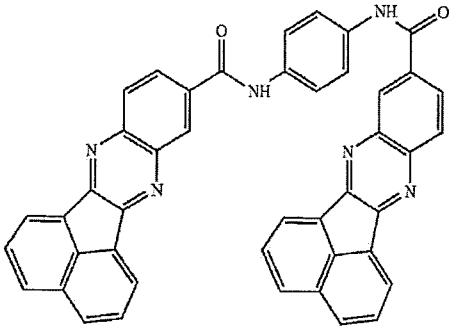
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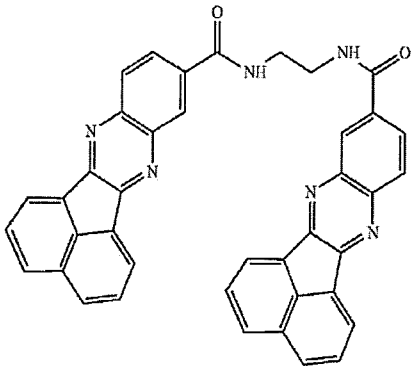
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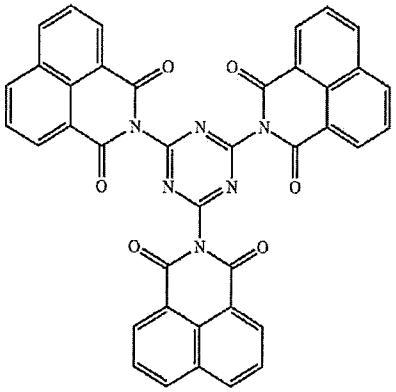
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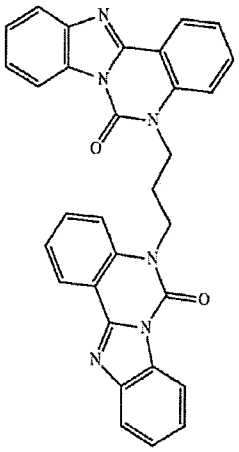
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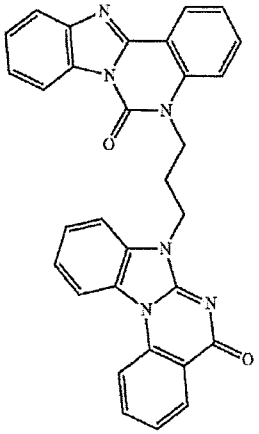
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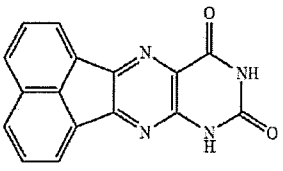
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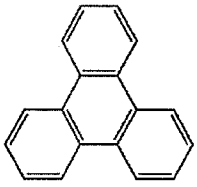
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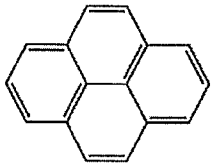
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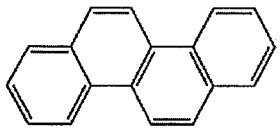
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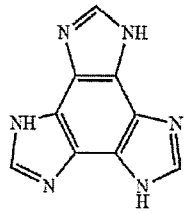
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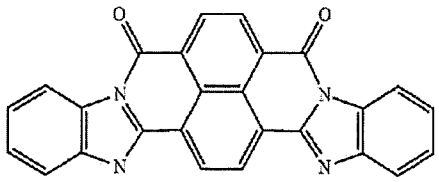
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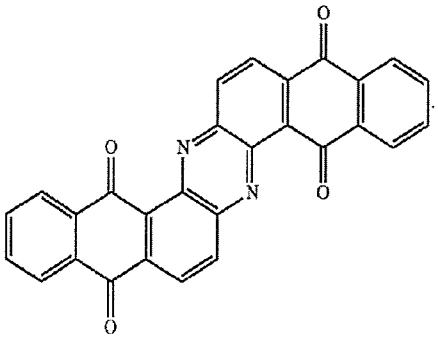
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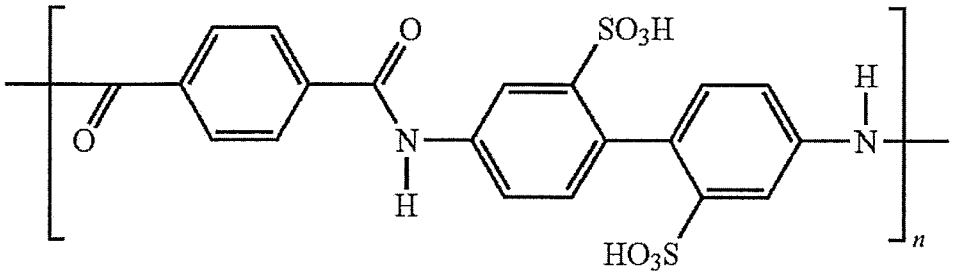


28. A self-healing capacitor according to claim 27 wherein the modifying functional groups are selected from the group consisting of alkyl, aryl, substituted alkyl, and substituted aryl.

29. A self-healing capacitor according to claim 1, wherein the dielectric layer comprise a compound selected from the group consisting of fluorinated alkyls, polyethylene, poly-paraphenylene terephthalamide, poly(vinylidene fluoride-hexafluoropropylene), polypropylene, fluorinated polypropylene, and polydimethylsiloxane.

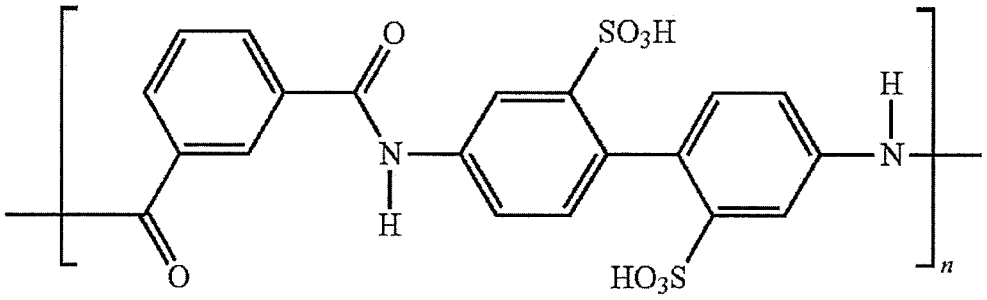
30. A self-healing capacitor according to claim 1, wherein the dielectric layer comprises a polymeric material formed on the basis of water-soluble polymers which are selected from structures 42 to 47:

42



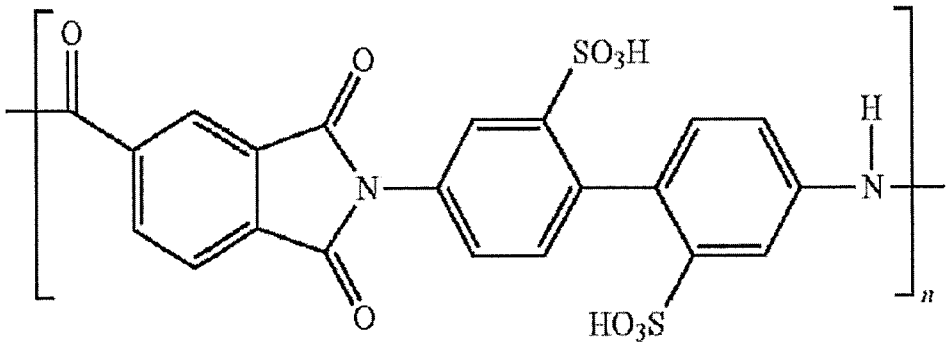
poly(2,2′-disulfo-4,4′-benzidine terephthalamide)

43



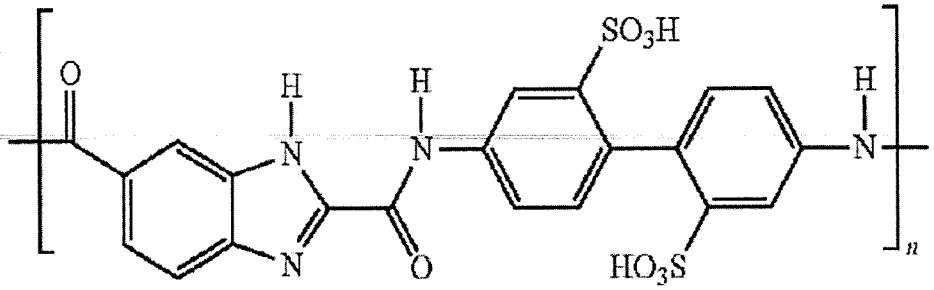
poly(2,2′-disulfo-4,4′-benzidine isophthalamide)

44



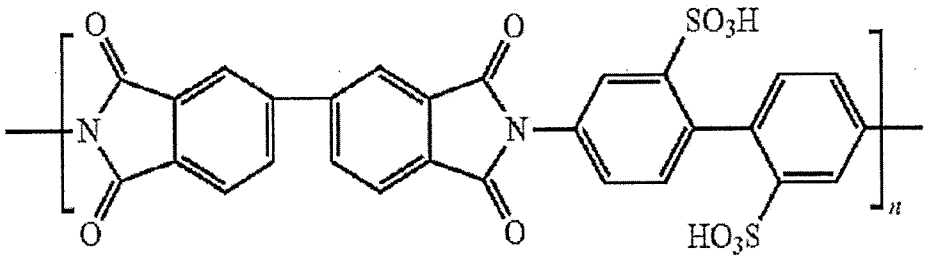
poly(2,2′-disulfo-4,4′-benzidine 1,3-dioxo-isoindoline-5-carboxamide)

45



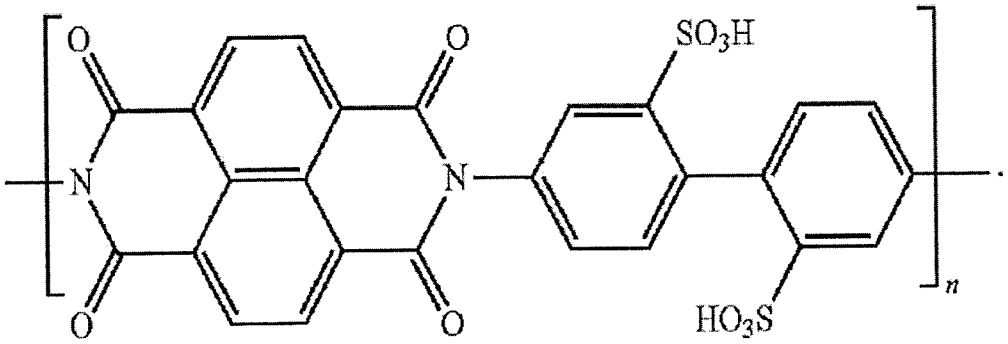
poly(2,2′-disulfo-4,4′-benzidine 1H-benzimidazole-2,5-dicarboxamide)

46



poly(2,2′-disulfo-4,4′-benzidine 3,3′,4,4′-biphenyl tetracarboxylic acid diimide)

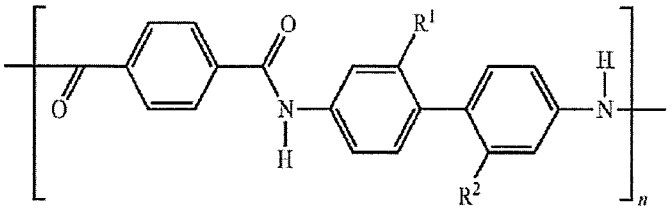
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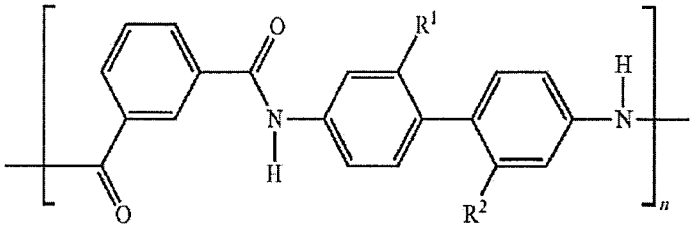
poly(2,2'disulpho-4,4'benzidine 1,4,5,8-naphtalen tetracarboxylic acid diimide)

31. A self-healing capacitor according to claim 1, wherein the dielectric layer comprises a polymeric material formed on the basis of polymers soluble in organic solvents which are selected from structures 48 to 53:

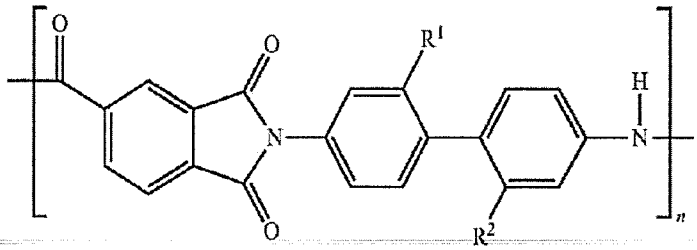
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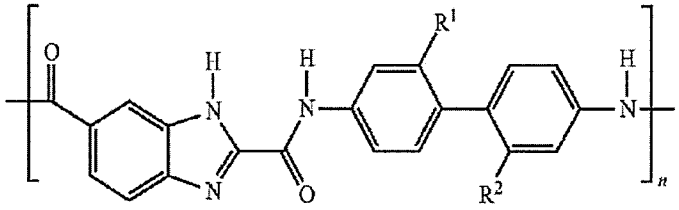
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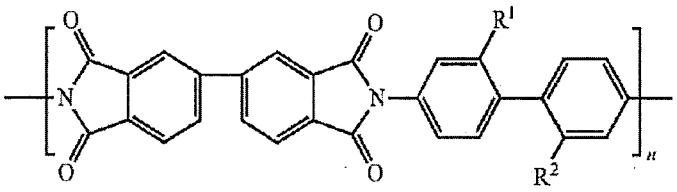
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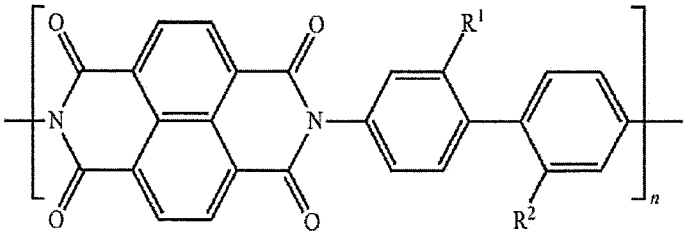
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52



53



wherein each wherein each R^1 and R^2 is independently selected from alkyl, aryl, substituted alkyl, and substituted aryl.

32. A self-healing capacitor according to claim 1, wherein the dielectric layer is crystalline.

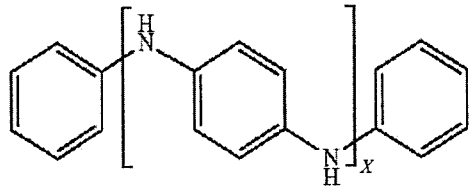
33. A self-healing capacitor according to claim 1, wherein the dielectric layer comprises a colloidal composite with a micro-dispersion of electro-conductive nano-particles in an insulator matrix.

34. A self-healing capacitor according to claim 33, wherein the electro-conductive nano-particles comprise electro-conductive oligomers.

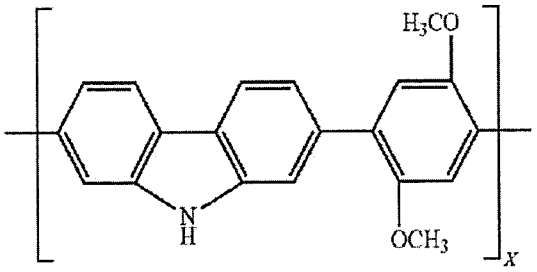
35. A self-healing capacitor according to claim 34, wherein a longitudinal axis of each of the electro-conductive oligomers is directed perpendicularly in relation to an electrode surface.

36. A self-healing capacitor according to claim 34, wherein the electro-conductive oligomers are selected from structures 54 to 60:

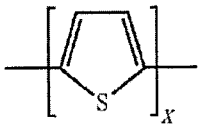
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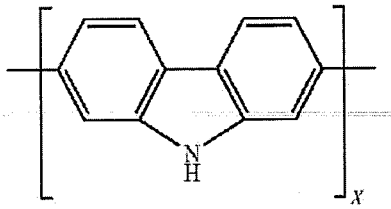
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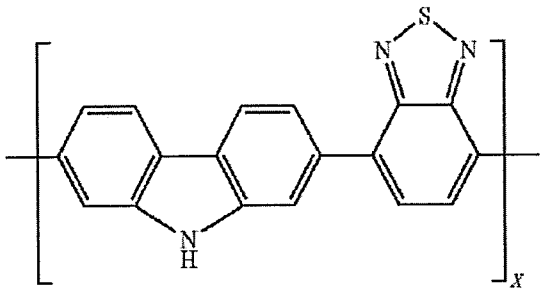
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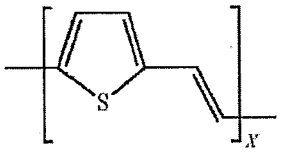
57



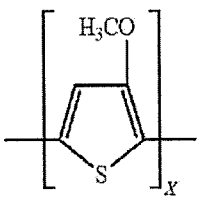
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59



60



wherein X=2, 3, 4, 5, 6, 7, 8, 9, 10, 11 or 12.

37. A self-healing capacitor according to claim 34, wherein each of the electroconductive oligomers further comprises substitute groups and has the following general structural formula II:

$$(\text{electroconductive oligomer})\ R_q \qquad \text{(II)}$$

wherein R is a substitute group, and q is a number that is greater than or equal to zero.

38. A self-healing capacitor according to claim 37, wherein each R is independently an alkyl, aryl, substituted alkyl, or substituted aryl, and any combination thereof.

39. A self-healing capacitor according to claim 33, wherein a material of the insulator matrix is selected from the group consisting of poly (acrylic acid) (PAA), poly(N-vinylpyrrolidone) (PVP), poly(vinylidene fluoride-hexafluoropropylene) [P(VDF-HFP)], ethylene propylene polymers, which include ethylene propylene rubber (EPR) and ethylene propylene diene monomer (EPDM), and silicone rubber (PDMSO) such as dimethyldicloro siloxane, dimethylsilane diol, and polydimethyl siloxane.

40. A self-healing capacitor according to claim 1, wherein said dielectric layer comprises a surfactant selected from: dodecylbenzene sulfonate (DBSA), polyoxyethylene glycol alkyl ethers, polyoxypropylene glycol alkyl ethers, polyoxyethylene glycol octylphenol ethers, polyoxyethylene glycol sorbitan alkyl esters, sorbitan alkyl esters, and dobecyldimethylamine oxide.

41. A self-healing capacitor according to claim 1, wherein said dielectric layer comprises a material selected from the group consisting of oxides, nitrides, oxynitrides and fluorides.

42. A self-healing capacitor according to claim 1, wherein said dielectric layer comprises a material selected from the group consisting of SiO_2, HfO_2, Al_2O_3 and Si_3N_4.

43. A self-healing capacitor according to claim 1, wherein the first electrode and the second electrode comprise the metal foam.

44. A method of producing a self-healing capacitor, comprising:

(a) applying an electric voltage across a first electrode and a second electrode that are separated by a dielectric layer, which applying comprises a gradual enhancement of the electric voltage to achieve electric breakdown, wherein at least one of the first and second electrodes includes a metal foam;

(b) applying an electric field across the first electrode and the second electrode to form electrically conductive channels with exit points on opposing surfaces of the dielectric layer;

(c) applying a current through the first and second electrodes to (i) induce Joule heating in at least one of the first and second electrodes and (ii) form local contact breakers in at least one of the first and second electrodes, which local contact breakers are formed adjacent or in proximity to the exit points; and

(d) terminating the application of the current upon formation of the local contact breakers.

45. The method of claim 44, wherein the application of the current is terminated upon when a sufficient amount of metal has evaporated from at least one of the first and second electrodes to form the local contact breakers.