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(54) **BUSHING COMPRISING A SEMICONDUCTIVE PAINT FOR FOIL EDGE STRESS REDUCTION**

(57) A bushing for high voltage applications comprises a conductor surrounded by at least one foil (22) of conductive material, where the foil has an edge over which a layer (26) of semiconductive paint stretches. The semiconductive paint comprises flakes of thermally re-

duced graphene oxide as a field grading material having a conductivity that varies with electrical field strength. The layer (26) has a thickness and the flakes have at least one width, where the thickness is smaller than the width.

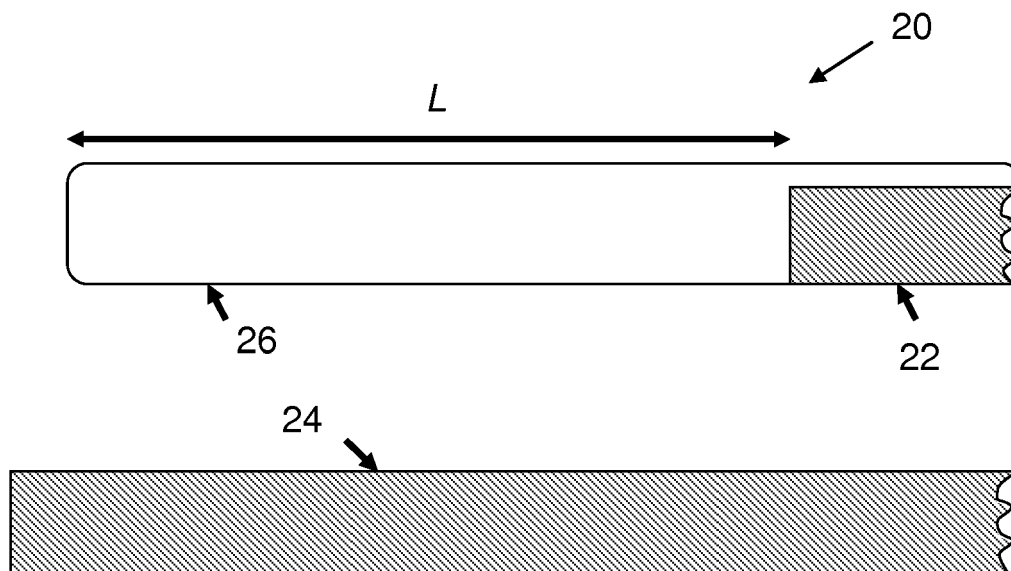


Fig. 2

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Description

FIELD OF INVENTION

[0001] The present invention generally relates to high voltage equipment. More particularly the present invention relates to a bushing for high voltage applications.

BACKGROUND

[0002] Graphene Oxide is a material that has become of interest to use in a number of different power system applications.

[0003] One experimental study that has been made of the material is disclosed in WO 2013/033603, where reduced graphene oxide was distributed in a polymer and the field grading properties investigated, i.e. the ability of the material to change conductivity in dependence of the applied electrical field. Due to the way graphene oxide was mixed with the polymer the electrical field dependency was observed to be isotropic.

[0004] The above-mentioned document also describes a number of application areas where the material can become useful, one such area being machines bushings.

[0005] In some instances, such as at high voltage ratings, so-called condenser bushings are frequently used in order to allow a conductor to penetrate a metallic wall and where the potential difference between conductor and wall is large. In condenser bushings cylindrical metallic foils, having different radii, are placed concentrically around an inner conductor. By varying the foil lengths, such that the foils close to the inner conductor are longer than those further out, a significantly more homogeneous electric field is created leading in turn to a reduction of the maximum field stress.

[0006] In this manner the probability for breakdown and failure can be drastically lowered.

[0007] As the voltage ratings become higher, the bushing size increases. The footprint, weight, and cost also increase accordingly. It is therefore highly desirable to limit the size by distributing the field stress as evenly as possible and to avoid regions with locally excessive field levels. This fact, together with the observation that bushings are one of the most highly stressed components in the power distribution chain, implies that their design is crucial for the economy and reliability of any high voltage power distribution network.

[0008] A bushing is particularly sensitive in the vicinity of the foil edges. With a given potential difference between a foil and its closest neighbor, the maximum electric field is found just at the edge of the foil. The metallic foils in a condenser bushing are usually very thin, of the order of 10-100 μm , and therefore the field enhancement can be quite large. It is therefore of interest to reduce these stresses.

[0009] One document that describes the use of graphene oxide in relation to foil edges is WO 2014/206435.

In this document graphene oxide is used in a material where the degree of reduction varies so that a permanent gradient exists in the electrical conductivity of the material. Thereby the conductivity in one part of the material becomes higher than in another. There is thus a step-wise change between the conductivities. A bridging element with these properties is obtained using an annealing method where graphene oxide is irradiated with laser light and the bridging element is then used at a foil edge of a bushing.

[0010] There would, in view of what is mentioned above be of interest to reduce the stress on a foil edge through using graphene oxide that obtains a smoother conductivity variation beyond the foil surface with a limited effect on the bushing size.

SUMMARY OF THE INVENTION

[0011] One object of the present invention is to provide a bushing that addresses the problem of reducing foil edge stress without increasing the bushing size.

[0012] This object is according to the present invention obtained through a bushing for high voltage applications comprising a conductor surrounded by at least one foil of conductive material, where the foil has an edge over which a layer of semiconductive paint stretches, where the semiconductive paint comprises flakes of thermally reduced graphene oxide as a field grading material having a conductivity that varies with electrical field strength. The layer has a thickness and the flakes have at least one width, where the thickness of the layer is smaller than the width of the flake.

[0013] The present invention has a number of advantages. In particular, it provides excellent reduction of foil edge stresses and this is achieved with negligible increase in bushing size. In addition there is a reduced need of field grading material in the paint.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention will in the following be described with reference being made to the accompanying drawings, where

fig. 1 schematically shows a bushing with an inner conductor surrounded by a field reducing volume comprising a number of foils, where one section of the field reducing volume has been indicated, fig. 2 schematically shows a side view of parts of two neighboring foils in the indicated section, where one of the foils has been extended with a layer of semiconductive paint, fig. 3 schematically shows a flake of graphene oxide used in the semiconductive paint, fig. 4 shows the dependence of conductivity on electrical field strength for a number of different types of graphene oxide flakes, fig. 5 schematically shows a number of interconnect-

ed flakes in the layer of semiconductive paint, fig. 6 schematically shows how the maximum electrical field strength depends on the low-field conductivity σ_0 for two different paints at two different lengths of extension layer beyond the foil edge, and fig. 7 shows a view from above of solid insulation used in the bushing and on which a layer of semiconductive paint has been applied.

DETAILED DESCRIPTION OF THE INVENTION

[0015] The present invention concerns a bushing for use in high voltage environments, such as high voltage power transmission environments. A bushing may as an example be a transformer bushing used for insulating the high voltage conductor from the grounded transformer housing. It may also be a wall bushing such as a bushing passing through a wall of a building, for instance a converter hall.

[0016] Fig. 1 schematically shows a bushing 10 comprising a central inner conductor 12 surrounded by a field reducing volume 18 comprising a number of cylindrical foils 14 of electrically conducting material, such as foils of Aluminum. The inner conductor 12 is thereby surrounded by at least one foil of conductive material, which may have a thickness in the range of 10 - 100 μm . The foils 14 may be coaxial with the conductor 12 but have different radii. Thereby the conductor 12 may also define an axis that the foils 14 surround. The foils 14 may be separated from each other and the inner conductor 12 by gaps, where a gap may as an example have a width of 250 μm . In these gaps electrical insulation may be provided, which insulation may comprise solid insulation as well as fluid insulation. Solid insulation may be cellulose, while fluid insulation may be transformer oil. Thereby the solid insulation may also be immersed in the fluid insulation. In the figure, there is also a flange 16 connected to the outermost foil.

[0017] The boundary points or edges of the above-mentioned foils are furthermore equipped with a layer of semiconductive paint, which paint comprises a field grading material. One region 20 of the field reducing volume 18 comprising parts of two foils where such a semiconductive paint has been applied is also indicated in fig. 1.

[0018] Fig. 2 schematically shows the region 20 with parts of the two foils 22 and 24, where the upper foil 22 has been provided with a layer of semiconductive paint 26 comprising field grading material. The upper foil 22 has a foil thickness FO_T , which thus may be 10 - 100 μm . The layer 26 is applied on top of the upper foil 22, i.e. on a surface facing away from the previously mentioned central conductor and also extends beyond the edge of this foil 22 in a first direction in parallel with the axis of the inner conductor. The layer 26 is thereby aligned with an upper foil surface facing away from the conductor 12 and also stretches over the edge. Moreover, the layer 26 may stretch away from the foil edge in a direction that is parallel with the axis defined by the inner conductor. The

layer 26 extends a distance L beyond the edge of the foil 22. It is thereby aligned with and covers the foil edge. The paint thereby has a first thickness L_T above the foil and a second thickness $L_T + FO_T$ in the area stretching away from the foil. The semiconductive paint comprises a field grading material (FGM), i.e. a material that has a field-dependent conductivity (or permittivity). This FGM material redistributes the electric field and reduces the maximum stress on the foil edge.

[0019] Even though only one foil is shown as being provided with the layer 26 of semiconductive paint, it should be realized that more foils and with advantage all may be provided with such a layer. Moreover, a foil will have a second edge at an opposite end of bushing. It should be realized that this end may in a similar manner be provided with a layer of semiconductive paint stretching out beyond the edge in a second direction in parallel with the axis of the inner conductor, which second direction is opposite to the first direction.

[0020] The semiconductive paint is such that it has a conductivity that increases with the electrical field strength. Through this property the electrical field strength will be gradually lowered away from the foil edge leading to lower stresses on it. Due to the shape of the flakes, the electrical conductivity in the perpendicular direction, which is radially away from the central axis of the inner conductor, is significantly lower compared to in the direction along the length of the foil and may even lack dependence of the electrical field strength.

[0021] According to aspects of the invention the enhanced field stress at the foil end edges of a high voltage condenser bushing is reduced through the paint being applied in a thin layer and using thermally reduced graphene oxide as a field grading material (FGM).

[0022] Traditionally FGMs have been made based on a percolated network of semiconductive particles, such as SiC or ZnO, in a polymer matrix. In practice, however, it has been difficult to physically produce FGM layers sufficiently thin and having the optimal material parameters required. According to percolation theory, around 17 vol% of spherical particles are required to create a continuous network in the three-dimensional systems of interest. Since the density is significantly higher for ZnO ($\rho = 5.6 \text{ g cm}^{-3}$) and SiC ($\rho = 3.2 \text{ g cm}^{-3}$) compared to the typically used polymers (Silicone rubber, EPDM, Epoxy resins; $\rho \sim 1 \text{ g cm}^{-3}$) this means that the materials are filled with at least 50 wt% of the particles, resulting in poor mechanical properties (low elongation of break and low tear resistance). In addition the particle diameter of the SiC ranges between 1 - 30 μm , most commonly 3 - 10 μm . The contact resistance between the grains are responsible for the nonlinear conductivity. In ZnO microvaristors the nonlinearity is an intrinsic property of the interior of the filler particles alone, and the particle contact resistance is low. The diameter of the microvaristors ranges between 10 to several hundred micrometers. A consequence is that it is not possible to produce very thin layers (<10 μm) that at the same time are mechanically

robust and have homogeneous properties. Furthermore, any attempt to apply a too thick layer, e.g. in the form of a commercially available FGM tape for machine insulation (thickness 0.1 - 0.3 mm) will result in "bumps" in the winding layers near the foil edges. Such irregularities will create small voids where harmful partial discharges can occur, eventually leading to material fatigue and local breakdown.

[0023] Therefore, the field grading material of the paint is according to aspects of the invention based on graphene oxide.

[0024] Graphene oxide is provided in flakes. Fig. 3 schematically shows the generic geometry of one such flake of graphene oxide having a flake width F_{W1} , where this width, which may be the diameter of the flake, may be roughly 1 μm . The flake width may generally be in the range 0.5 - 10 μm . A flake may also have a thickness F_T that is about 1 nm. The flake may generally have a thickness F_T in the range 0.5 - 10 nm and thereby the flake will be more or less two-dimensional. It may thus be essentially two-dimensional.

[0025] It has been experimentally shown that FGMs based on graphene oxide indeed exhibit a strong nonlinear behavior as regards the field-dependent conductivity, see Z. Wang, J.K. Nelson, H. Hillborg, S. Zhao, and L.S. Schadler, "Graphene Oxide Filled Nanocomposite with Novel Electrical and Dielectric Properties", Adv. Mater., Vol. 24, No. 23, pp. 3134-3137, 2012. There, 3 - 5 phr (parts by weight per 100 parts of silicone resin mixture) of graphene oxide was thermally reduced at different temperatures, and subsequently dispersed in a silicone matrix followed by crosslinking to create a silicone rubber. Fig. 4 shows measured conductivity curves for four FGMs with graphene oxide isotropically dispersed in a polymer matrix, from the above mentioned document. The FGMs are based on silicone rubber filled with 3 or 5 wt% of thermally reduced graphene oxide. The graphene oxide flakes were reduced at 70, 120 or 140 °C. In fig. 4 the diamond shaped markers are related to flakes with 5 wt% graphene reduced at 70 °C, the square shaped markers are related to flakes with 5 wt% graphene reduced at 120 °C, the circle shaped markers are related to flakes with 3 wt% graphene reduced at 120 °C and the triangle shaped markers are related to flakes with 3 wt% graphene reduced at 140 °C.

[0026] The onset of non-linearity increased with increasing reduction temperature. The investigated material is based on a high aspect ratio filler which is randomly oriented in a polymer matrix. Thanks to the high aspect ratio, percolation is obtained at around 3 wt% (1.5 vol%).

[0027] From this investigation of graphene oxide, which is also discussed in previously mentioned WO 2013/033603, it can thus be seen that the material is promising to be used as field grading material. Therefore aspects of the invention are directed towards using graphene oxide in the semiconductive paint. The paint thus comprises flakes of thermally reduced graphene oxide as a field grading material having a conductivity that

varies with electrical field strength.

[0028] The paint may more particularly comprise the above-mentioned flakes dispersed in a suitable polymer resin (binder) and solvent, where it is possible that the amount of graphene oxide is 1 - 5 wt %.

[0029] The paint may be deposited onto the foil and possibly also the solid insulation between it and a neighbouring foil by spraying or printing, for instance with a thickness of 10 - 200 nm. The first thickness L_T may thus be 10 - 200 nm. Since the two-dimensional (2D) graphene oxide flakes are very small (typically 1 nm in thickness and 1 x 1 μm in length and width) compared to SiC and ZnO particles it is possible to produce thin and homogeneous paint layers. It is possible that the flake width is at least twice the layer thickness. It may be even be preferred that the flake width is at least four times the layer thickness. As can be seen in fig. 2, it is possible that this relationship is only valid for the part of the layer of paint 26 that is provided on top of the foil 22, but not for the part that stretches out over the edge. The relationship may thus be valid at least above the foil. Moreover, it can be noted that the graphene oxide flakes can be individually dispersed, but also in the form of multiple layers (graphitic structure). Thereby the size increase of the bushing caused by the introduction of the paint is negligible.

[0030] It is also possible that the layer thickness L_T is at least twice the flake thickness F_T . It is more particularly possible that the layer thickness L_T is 2 to 200 times larger than the flake thickness F_T in order to obtain the graphitic structure. It is here possible that the range is only valid for the part of the layer of paint 26 that is provided on top of the foil 22 and not for the part that stretches out over the edge.

[0031] The part of the layer of paint 26 that stretches out from the foil edge would then have the second thickness $L_T + FO_T$, which can be considered to be equal to FO_T . In this area, the layer thickness would thus essentially have the same thickness as the foil. Moreover, the thickness of this part of the layer 26 would be 1000 - 200000 times larger than the flake thickness F_T . The layer thickness might in this area also be 1 - 200 times higher than the flake width F_w .

[0032] Furthermore, due to the fact that the flake width is considerably larger than the layer thickness L_T , the flakes 28 will be essentially oriented along the length of the layer of paint within this layer 26. The graphene oxide flakes may thus be partially aligned along the surface due to the thin layer thickness and the larger flake size. This is schematically indicated in fig. 5. Thereby the nonlinear field-dependent conductivity is obtained along this surface. Since the conductivity perpendicular to the layer is likely to be lower, an anisotropic conductivity results. Consequently a lower filler fraction is required, compared to randomly oriented graphene oxide flakes, thus the percolation threshold may be < 1.5 vol%.

[0033] This semiconductive paint can then be used for reducing the electric field stress along the foil edges in

HV bushings. The semiconductive paint can be applied in desired patterns using printing or spraying techniques.

[0034] This kind of semiconductive ink or paint can also be very useful for grading the electric stress along printed conductive electrodes.

[0035] Furthermore, when allowing for detailed tailoring of the conductivity parameters σ_0 (the low-field constant conductivity), E_c (the threshold field above which nonlinear increase starts), and α (the exponent of nonlinear increase), it becomes possible to further reduce the field stress and to make this reduction more robust.

[0036] An example is shown in Fig. 6, illustrating the results from a simulation study. This example is related to a considerably thicker layer of semiconductive paint than described in the invention. However, the general behavior is the same, as are the conclusions. Fig. 6 shows the maximum field stress, $\max(E)$, along the surface of the layer of semiconductive paint plotted against σ_0 for two different values each of E_c ($E_c = 0.4$ kV/mm and $E_c = 6.0$ kV/mm) and L ($L = 1$ mm and $L = 5$ mm), where L is the length of the layer of paint beyond the foil edge. The curves C_1 and C_2 correspond to $E_c = 6.0$ kV/mm, where C_1 is for $L = 1$ mm and C_2 for $L = 5$ mm. Because E_c is higher than the actual electric field, the material basically behaves as a linear FGM, i.e. the conductivity is approximately constant and equal to σ_0 . The curves C_3 and C_4 , on the other hand, represent $E_c = 0.4$ kV/mm, where C_3 is for $L = 1$ mm and C_4 for $L = 5$ mm, implying that the layer is driven far into the nonlinear regime. In the limit of very small σ_0 the FGM layer has no effect and the maximum field stress occurs at the foil edge. At very high σ_0 , on the other hand, the FGM layer is highly conducting and effectively acts as an extension of the foil. The corresponding maximum field is therefore found at the edge of the FGM layer. In the example Fig. 6 refers to, the FGM layer is thicker (50 μm) than the foil (5 μm), resulting in different stress values in the two limits. It is seen that by varying σ_0 , E_c , and L it is possible to reach very low field stress values at minima which are broad, i.e. rather insensitive to changes in the material parameters. By choosing σ_0 , or actually the product of σ_0 and the thickness of the layer, a few orders of magnitude smaller than the value corresponding to the minimum for the linear case (curves C_1 and C_2 in Fig. 6), a nearly optimal and robust stress reduction is achieved.

[0037] It should be mentioned that the three relevant material parameters σ_0 , E_c , and α can all be controlled by changing the material composition and/or the manufacturing process. The theoretical optimization thus described can consequently be employed to find physically realizable solutions that correspond to the desired electrical and thermal performance of the bushing.

[0038] Moreover, as the material is provided as a paint or an ink, it may be applied in an industrial printing process. It may as an example be printed on the solid insulating material before assembly of the bushing. An example of a layer of paint 26 being printed on solid insulation 30 is schematically shown in fig. 7.

[0039] A successful application of the above concept would imply the possibility to manufacture high voltage bushings that can withstand higher stress levels, both in regular operation and under transient conditions. Alternatively, for the same voltage rating the bushing can be made smaller, lighter, and less expensive. Moreover, through the use of a paint it is possible to obtain the desired field-grading properties in a simple way using established industrial production techniques, such as printing.

[0040] From the foregoing discussion it is evident that the present invention can be varied in a multitude of ways.

[0041] It shall consequently be realized that the present invention is only to be limited by the following claims.

Claims

1. A bushing (10) for high voltage applications comprising a conductor (12) surrounded by at least one foil (22) of conductive material, said foil having an edge over which a layer (26) of semiconductive paint stretches, said semiconductive paint comprising flakes (28) of thermally reduced graphene oxide as a field grading material having a conductivity that varies with electrical field strength, said layer (26) having a thickness (L_T) and said flakes having a width (F_w), wherein said thickness (L_T) of the layer (26) is smaller than said width (F_w) of the flakes at least above the foil (22).
2. The bushing (10) according to claim 1, wherein said flake width (F_{w1}) is at least twice the layer thickness (L_T).
3. The bushing (10) according to claim 2, wherein said flake width (F_{w1}) is at least four times the layer thickness (L_T).
4. The bushing according to any previous claim, wherein the flakes have a flake thickness (F_T) and said layer thickness (L_T) is at least twice the flake thickness (F_T).
5. The bushing according to claim 4, wherein the layer thickness (L_T) is two to two hundred times larger than the flake thickness (F_T).
6. The bushing (10) according to any previous claim, wherein the layer thickness (L_T) is in the range 2 - 100 nm and the flake width (F_w) is in the range 0.5 - 10 μm .
7. The bushing (10) according to any previous claim, wherein the flakes (28) have a thickness in the range 0.5 - 10 nm thereby making them essentially two-dimensional and generally oriented within the layer

of paint along the length of the layer (26).

8. The bushing (10) according to any previous claim, wherein the paint comprises the graphene oxide at 1 - 5 wt%. 5
9. The bushing (10) according to claim 8, wherein the paint comprises a resin and a binder.
10. The bushing (10) according to any previous claim, wherein the layer (26) of paint is aligned with an upper foil surface facing away from the conductor (12) and stretches away from the foil edge in a direction that is parallel with an axis defined by the conductor. 10
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11. The bushing (10) according to any previous claim, further comprising solid insulating material (30) adjacent the foil (22), wherein the paint (26) is printed on the solid insulating material. 20
12. The bushing (10) according to any previous claim, wherein the foil (22) has a thickness in the range 10 - 100 μm . 25

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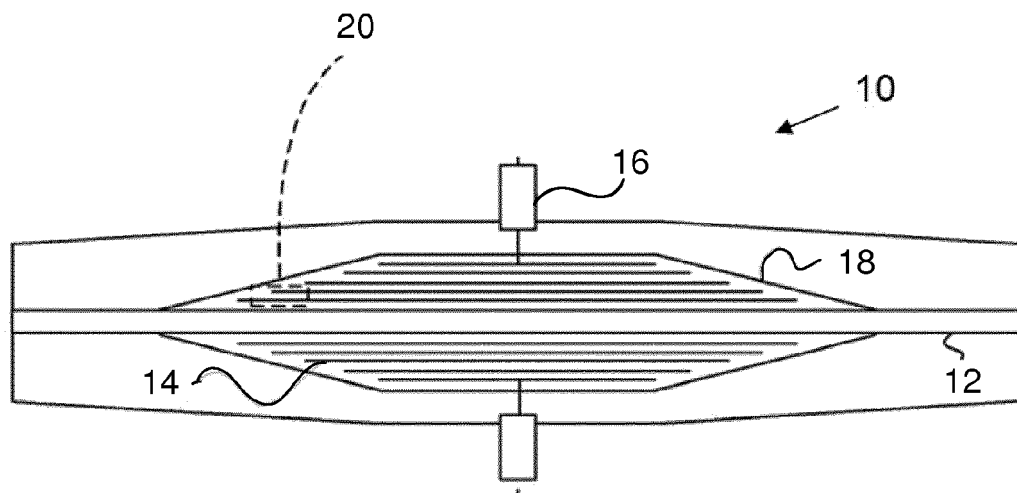


Fig. 1

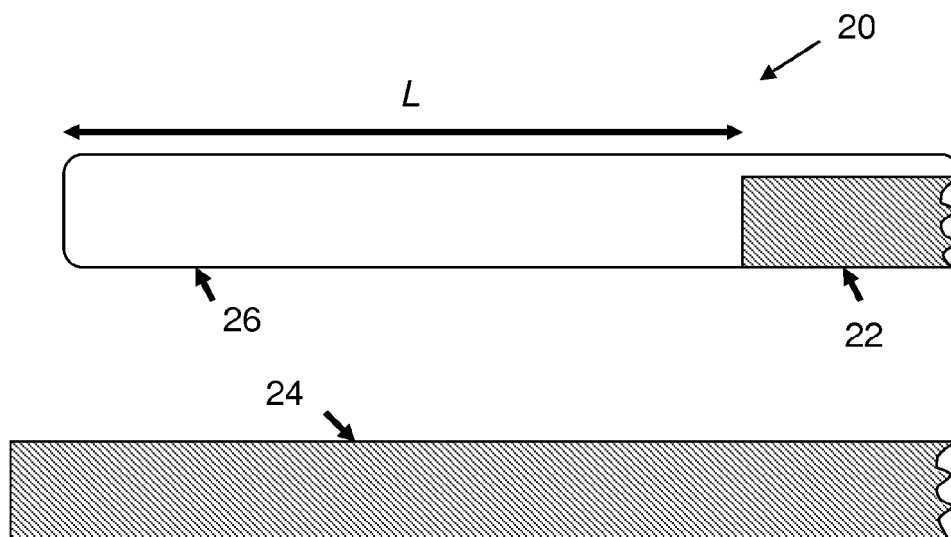


Fig. 2

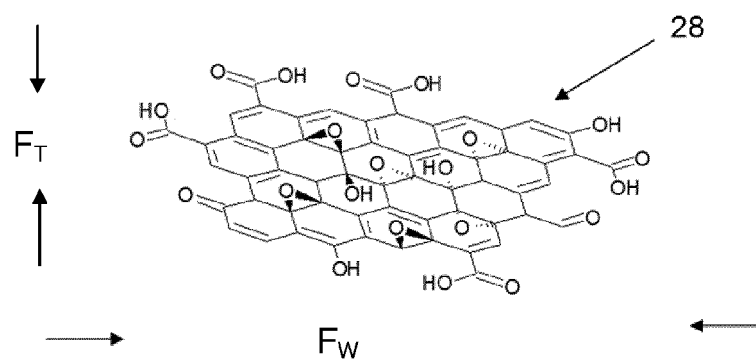


Fig. 3

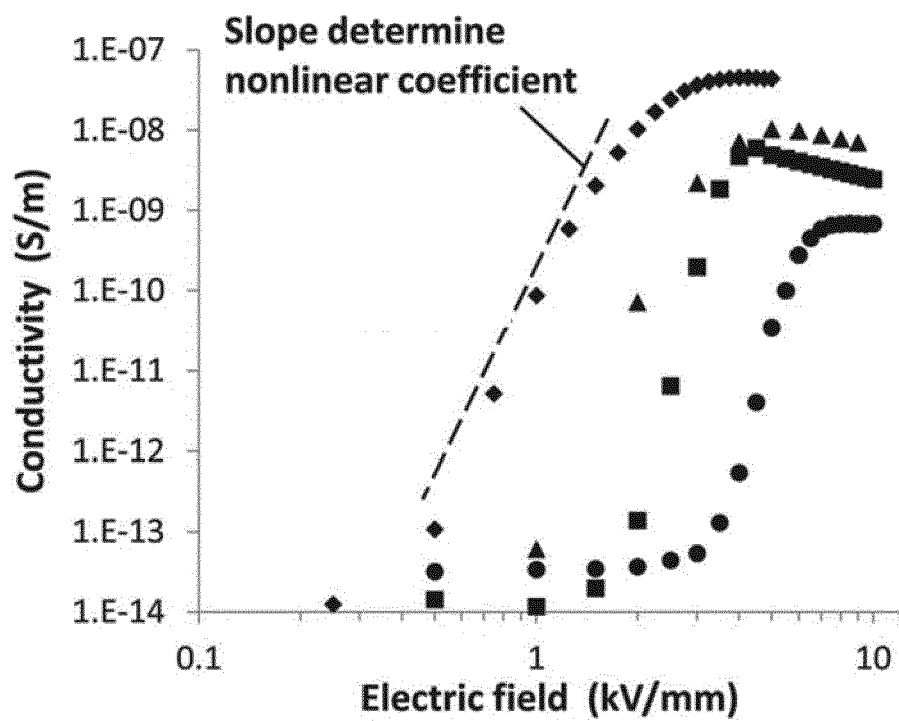


Fig. 4

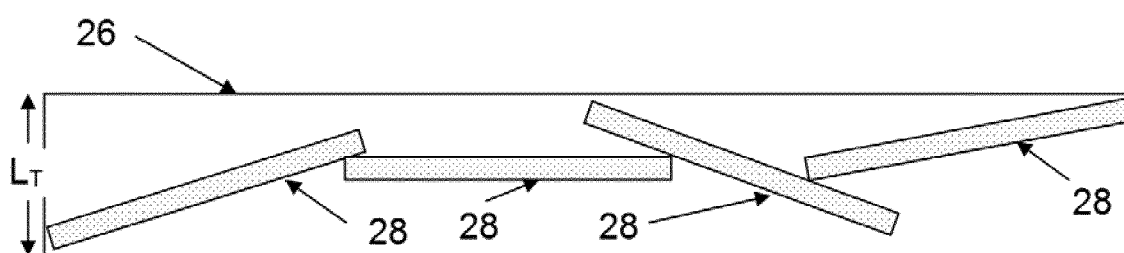


Fig. 5

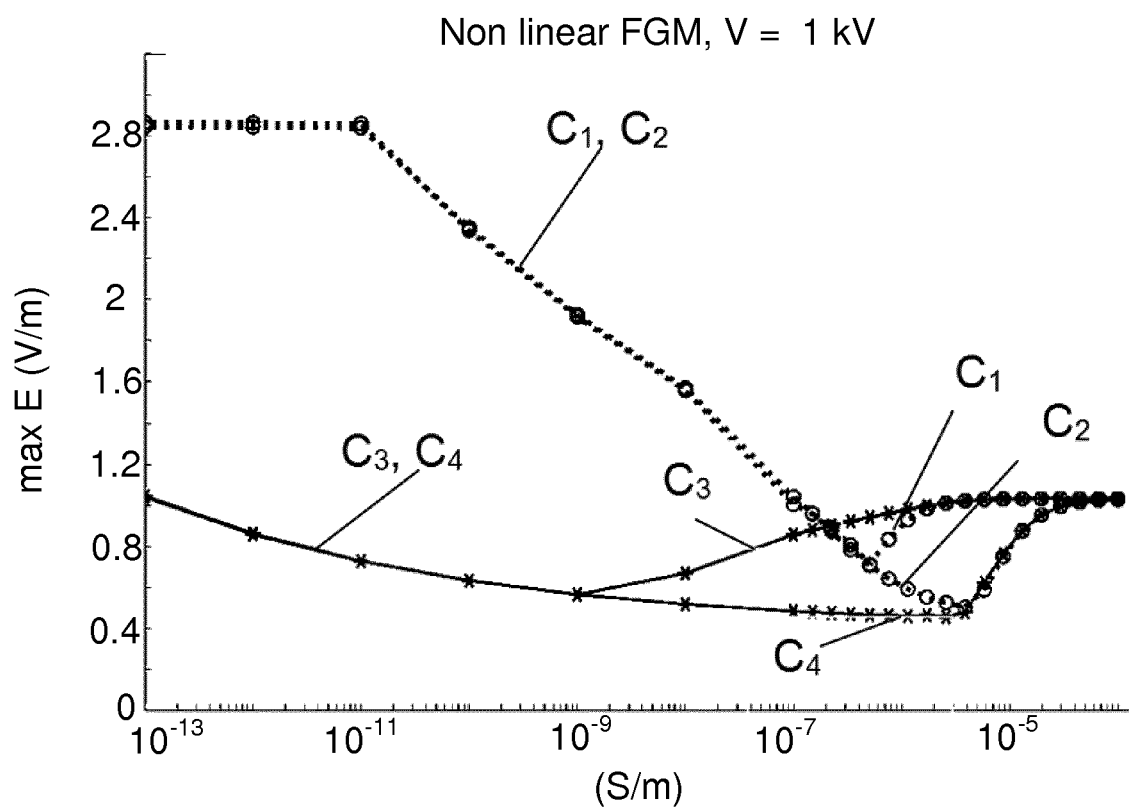


Fig. 6

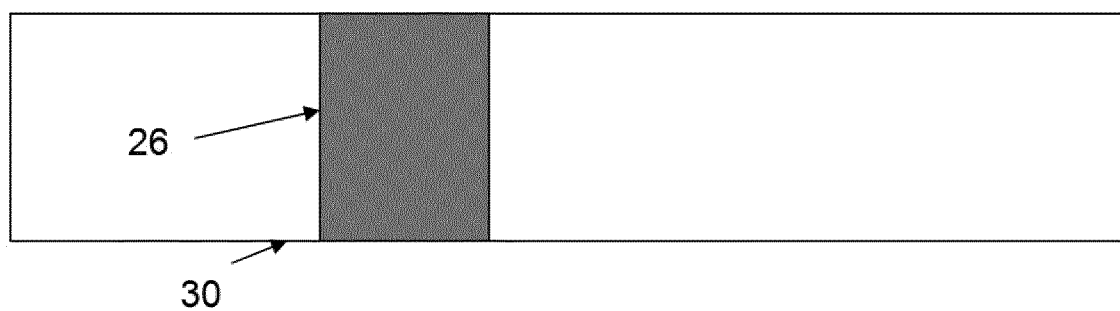


Fig. 7



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The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 5 July 2017	Examiner Lehnert, Andreas
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