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(54) **CONFORMAL ELECTRONIC DEVICE**

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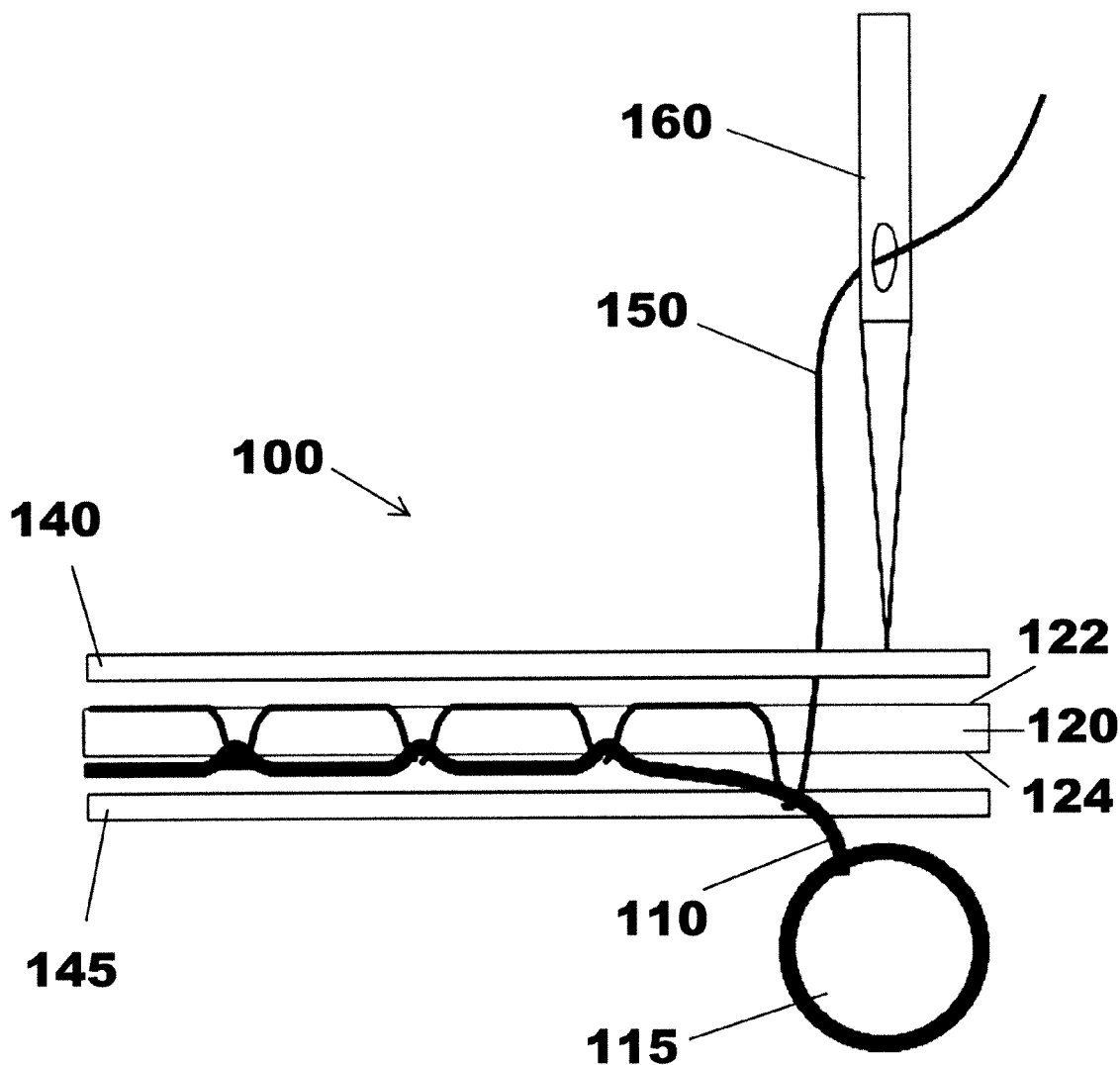
(57) **ABSTRACT**

A method for manufacturing a conformal electronic device includes securing an electrically-conductive fiber to a fabric or substrate using an assistant thread.

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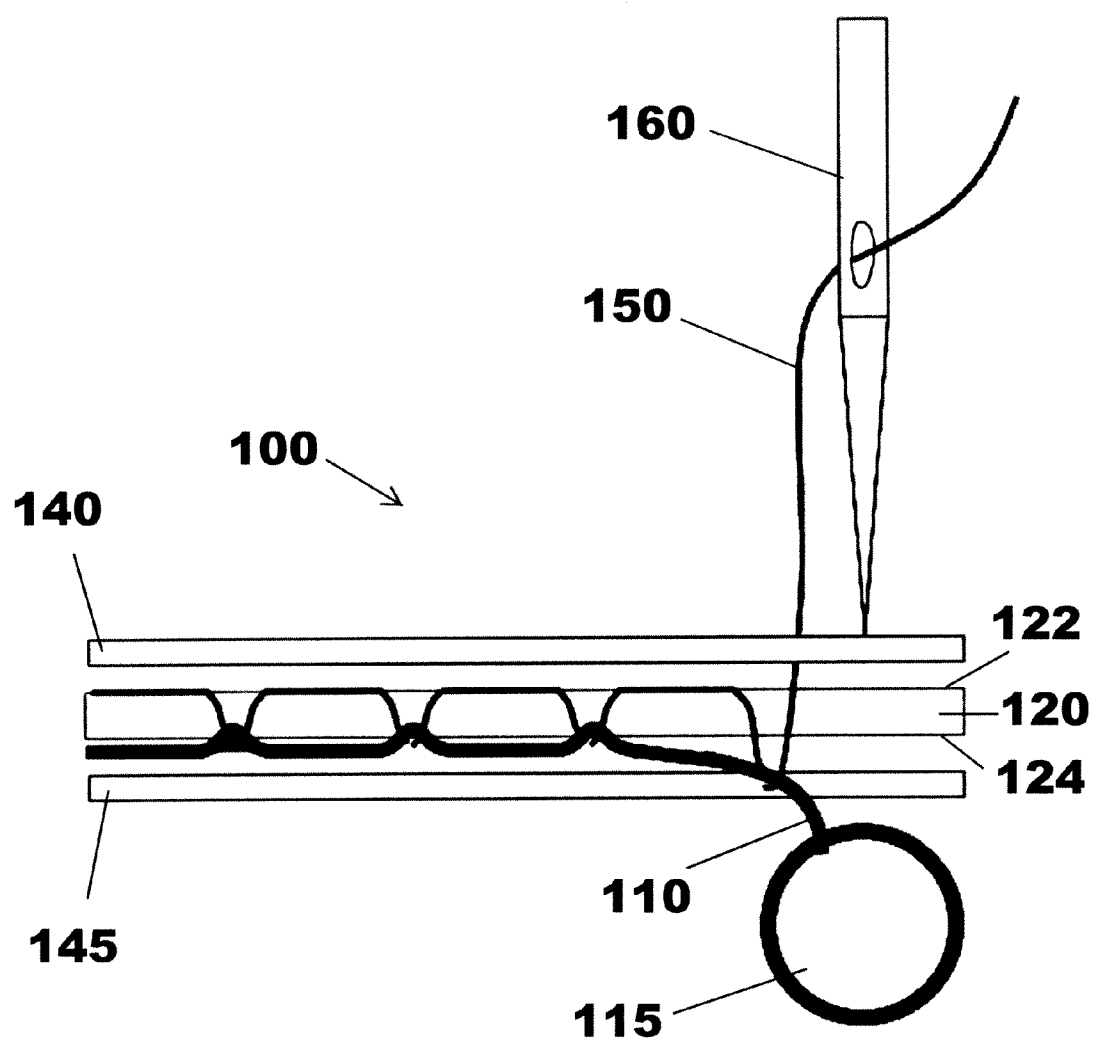


FIG. 1

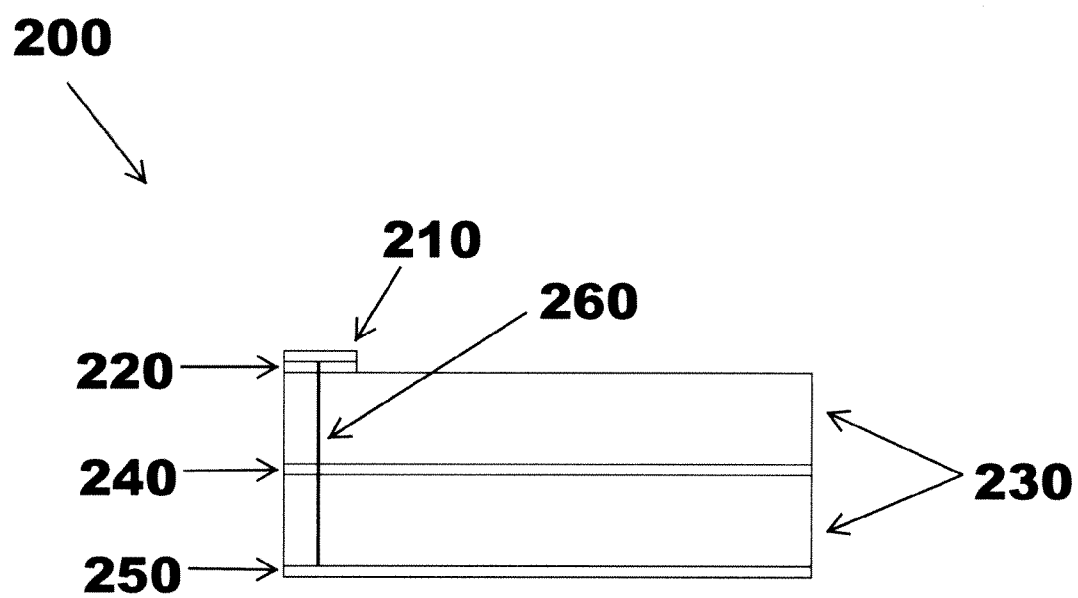


FIG. 2

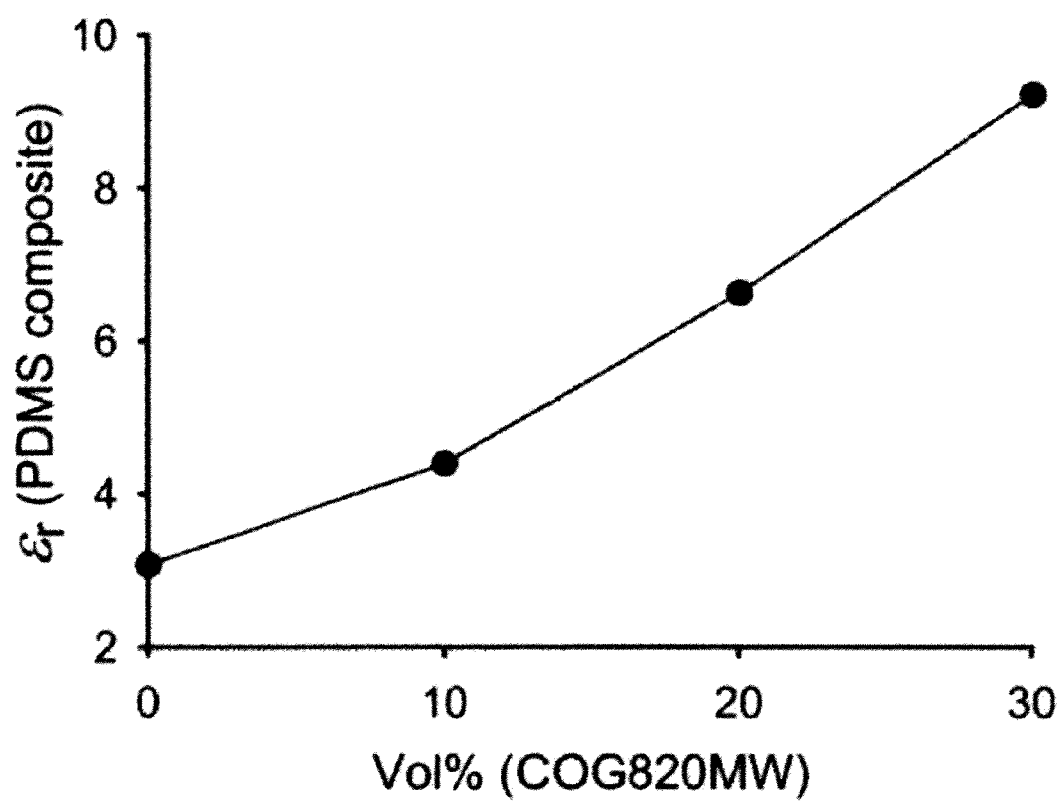


FIG. 3

CONFORMAL ELECTRONIC DEVICE

[0001] This application claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 61/434,479, filed Jan. 20, 2011. Ser. No. 61/434,479 is incorporated by reference herein in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Grant FA 9550-07-1-0462 awarded by the Air Force Office of Scientific Research (AFOSR). The government has certain rights in the invention.

BACKGROUND

[0003] The present disclosure relates to conformal electronic devices and methods for manufacturing the same. It finds particular application in conjunction with antennas, and will be described with particular reference thereto. However, it is to be appreciated that the present exemplary embodiment is also amenable to other like applications.

[0004] Conformal electronic devices have recently attracted considerable attention for various electromagnetic applications including wearable electronic devices and antennas for unmanned aerial vehicles. Conformal electronic devices must exhibit suitable electrical properties and performance while also providing mechanical conformity and flexibility. Previously known processes for manufacturing conformal electronic devices may yield mechanically or electrically deficient products and/or may be complicated and difficult to reproduce.

[0005] It would be desirable to develop new fabrication methods for manufacturing conformal electronic devices.

BRIEF DESCRIPTION

[0006] The present disclosure relates to methods for manufacturing conformal electronic devices. The methods comprise securing electrically-conductive fibers to a fabric or substrate using an assistant thread.

[0007] Disclosed in embodiments is a method for manufacturing a conformal electronic device. The method includes providing an electrically-conductive fiber in proximity to a first surface of a substrate; and sewing an assistant thread through the first surface, around the electrically conductive-fiber, and back through the first surface to secure the electrically-conductive fiber to the substrate.

[0008] The substrate may include a silicon-based polymer. The silicon-based polymer may be a polysiloxane or a polysilsesquioxane. The polysiloxane may be polydimethylsiloxane.

[0009] The substrate may further include a ceramic material dispersed in the silicon-based polymer. The ceramic material may be a titanate. The titanate may be a rare earth titanate.

[0010] The electrically-conductive fiber may include one or more electrically-conductive threads. Each thread may include a core and a conductive shell. The conductive shell includes a conductive material. The conductive material may be selected from carbon nanotubes and metals. The metal may be silver, copper, or nickel. The core may include an aramid fiber or an oxazole.

[0011] The sewing may be performed in a predetermined pattern using a digitized sewing machine.

[0012] The substrate may be pre-stretched prior to sewing.

[0013] The electronic device may further include a fabric layer between the substrate and the electrically-conductive fiber.

[0014] Also disclosed is another method of manufacturing a conformal electronic device. The method includes providing an electrically-conductive fiber in proximity to a first surface of a fabric; and sewing an assistant thread through the first surface, around the electrically conductive-fiber, and back through the first surface to secure the electrically-conductive fiber to the fabric to form an embroidered fabric.

[0015] The method optionally includes securing the embroidered fabric to a substrate. The substrate may include a silicon-based polymer matrix and a ceramic material dispersed within the silicon-based polymer matrix.

[0016] The electrically-conductive fiber may include one or more electrically-conductive threads. Each thread may include a core and an electrically-conductive shell. The shell includes a conductive material. The conductive material may be selected from carbon nanotubes and metals.

[0017] Further disclosed is another method for manufacturing a conformal electronic device. The method includes providing a predetermined digital pattern to a sewing machine; and embroidering the pattern onto a first surface of a substrate with an electrically-conductive fiber using an assistant thread from the sewing machine. The embroidering is performed by (a) providing a portion of the electrically-conductive fiber in proximity to a pattern section of the first surface of the substrate; (b) sewing the assistant thread from a second surface of the substrate through the first surface, around the portion of the electrically-conductive fiber, and back through the first surface to secure the portion of the electrically-conductive fiber to the pattern section of the substrate; and (c) repeating elements (a) and (b) for different portions of the electrically-conductive fiber and different pattern sections of the first surface of the substrate until the pattern is complete.

[0018] These and other non-limiting aspects and/or objects of the disclosure are more particularly described below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The following is a brief description of the drawings, which are presented for the purposes of illustrating the exemplary embodiments disclosed herein and not for the purposes of limiting the same.

[0020] FIG. 1 is a side-view of a conformal electronic device being manufactured in accordance with an exemplary method of the present disclosure.

[0021] FIG. 2 is a cross-sectional view of an exemplary electronic device of the present disclosure.

[0022] FIG. 3 is a graph illustrating the dielectric constant of composite materials including varying amounts of a ceramic material.

DETAILED DESCRIPTION

[0023] A more complete understanding of the processes and apparatuses disclosed herein can be obtained by reference to the accompanying drawings. These figures are merely schematic representations based on convenience and the ease of demonstrating the existing art and/or the present development, and are, therefore, not intended to indicate relative size and dimensions of the assemblies or components thereof.

[0024] Although specific terms are used in the following description for the sake of clarity, these terms are intended to refer only to the particular structure of the embodiments selected for illustration in the drawings, and are not intended to define or limit the scope of the disclosure. In the drawings and the following description below, it is to be understood that like numeric designations refer to components of like function.

[0025] The modifier “about” used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (for example, it includes at least the degree of error associated with the measurement of the particular quantity). When used with a specific value, it should also be considered as disclosing that value. For example, the term “about 2” also discloses the value “2” and the range “from about 2 to about 4” also discloses the range “from 2 to 4.”

[0026] The present disclosure relates to methods for manufacturing conformal electronic devices. The methods generally include securing an electrically-conductive fiber to a fabric or substrate using an assistant thread.

[0027] FIG. 1 is a side perspective view of an electronic device being manufactured with an apparatus 100 in accordance with an exemplary embodiment of the present disclosure. An electrically-conductive fiber 110 is fed to close proximity to a first surface 124 of a fabric or substrate 120 from an electrically-conductive fiber source 115. The fabric or substrate 120 is guided by a second guiding member 140 and a first guiding member 145. An assistant thread 150 is provided through a needle 160. The needle 160 enters the second surface 122 of the substrate 120, passes through the substrate 120, and emerges through the first surface 124. The assistant thread 150 and/or the electrically-conductive fiber 110 are arranged such that the assistant thread 150 surrounds a portion of the electrically-conductive fiber 110 on a side opposite the substrate 120. As the needle 160 is brought back through the substrate 120, the assistant thread 150 secures or couches the electrically-conductive fiber 110 to the first surface 124 of the substrate 120. The process may be repeated until a desired pattern or surface conductivity is achieved.

[0028] The electrically-conductive fiber source 115 may comprise a spool or a bobbin loaded with the electrically-conductive fiber 110. The electrically-conductive fiber 110 may have a diameter larger than the hole in the needle 160. In some embodiments, the diameter of the electrically-conductive fiber 110 is larger than the diameter of the needle 160. The guiding members 140 and 145, needle 160, and electrically-conductive fiber source 115 may be parts of a computerized sewing machine. In some embodiments, the sewing machine can receive a desired digital pattern and produce the pattern on the fabric or substrate 120 with the electrically-conductive fiber 110. The methods of the present disclosure may also be performed manually.

[0029] FIG. 2 is a cross-sectional view of an exemplary electronic device 200 of the present disclosure. The electronic device 200 includes an electrically-conductive fiber layer 210, an optional fabric layer 220, a substrate 230, an optional reinforcing layer 240, a ground plane 250, and a via hole 260 electrically connecting the fiber layer 210 to the ground plane 250.

[0030] The substrate 230 may comprise a polymer. The substrate may also comprise a ceramic material. In some embodiments, the ceramic material is dispersed in a matrix of the polymer to form a composite. In some embodiments, the

substrate has a thickness in the micrometer or centimeter range. The substrate may be pre-stretched prior to stitching. The term “pre-stretched” refers to the substrate being in a stretched position during stitching. Stitching on a pre-stretched substrate may be used to ensure that the electrically-conductive fiber will have sufficient leeway during subsequent stretching and relaxation of the substrate.

[0031] In some embodiments, the polymer is a liquid crystal polymer, Parylene-N, or a silicon-based polymer. Exemplary silicon-based polymers include polysiloxanes and polysilsesquioxanes. The polysiloxane may be polydimethylsiloxane (PDMS). PDMS can be used in flexible substrates and exhibits low dielectric loss ($\tan \delta$), high water resistivity, high temperature stability, high physical stability, and high chemical stability. PDMS is also a relatively low cost material and is relatively easy to use in fabrication processes. PDMS is also compatible with ceramic materials, such as dielectric ceramic powders. The density of PDMS is comparable to that of water and less than many other potential substrate materials which allows lighter-weight devices to be fabricated. This property may be important for wearable devices and aerospace applications in particular.

[0032] The ceramic material may comprise a titanate. Titanate powders exhibit relatively high relative permittivities (ϵ_r) at microwave frequencies. In some embodiments, the titanate is a rare earth titanate (RET).

[0033] The dielectric properties of the substrate may be tuned by varying the relative amounts of the polymer and the ceramic material. The ability to tune the dielectric properties of the substrate permits designing the substrate for a specific application depending on the application frequencies. For example, PDMS has an ϵ_r of about 3. By dispersing TAMTRON® COG820MW (commercially available from Ferro), in a PDMS matrix at varying concentrations of from 0 vol % to 30 vol %, the ϵ_r of the resultant composite material can be varied from about 3 to about 13. COG820MW is a barium neodymium titanate-based material containing bismuth. For example, at 10 vol % loading of COG820MW, an ϵ_r of about 4.2 and an overall $\tan \delta$ of less than 0.01 at 1 GHz can be achieved. This particular relationship between ceramic material loading and ϵ_r is specific to the polymer and ceramic materials used. Relationships for other material systems can be determined via experimentation.

[0034] Flexible polymer-ceramic substrates also provide versatile dimensions, e.g. micrometer and centimeter range dimensions, for printing highly detailed electronics.

[0035] The substrate may be formed by casting a substrate composition comprising a polymer and, optionally, an amount of a ceramic material sufficient to achieve desired dielectric properties. The composition is preferably homogeneously mixed to disperse the ceramic material in the polymer matrix prior to casting.

[0036] The substrate may be casted directly or tape-casted. In direct casting, the substrate composition is poured into a target mold. The mold is typically made of PMMA or glass, and preferably has smooth, flat edges. For a PDMS matrix, shrinkage is typically negligible after curing. Accordingly, the desired thickness of the final substrate can be marked on the mold for guidance. Direct molding may be performed for substrates having relatively small lateral dimensions, e.g. on the order of several cm.

[0037] Tape-casting is commonly used for thick film fabrication and low temperature co-fired ceramic (LTCC) processes. Tape-casting may be particularly suitable for sub-

strates having a thickness of 9 mm or less. In tape-casting, the substrate composition is poured into a film applicator. The applicator is glided smoothly across a flat supporting platform. The supporting platform may include glass or silicon. The thickness of the casted composition is controlled by the applicator blade gap, viscosity, and casting speed.

[0038] The casted substrate is optionally degassed and partially cured. Partial curing may be performed in an oven, on a hot plate, or at room temperature. The oven may be at a temperature of from about 50° C. to about 100° C., including about 60° C. The hot plate may be at a temperature of from about 70° C. to about 100° C., including about 80° C. The partial curing may last for a period of from about 15 to about 30 minutes, including from about 20 to about 25 minutes. The partial curing time period could be reduced if the PDMS had been precured. For example, if the PDMS was cured at room temperature for about 9 hours before casting, then the partial curing step length could be as short as 1.5 minutes.

[0039] In some embodiments, the electrically-conductive fiber layer **210** is secured directly to the substrate **230** by passing the assistant thread through the substrate **230**. A fabric layer **220** may be included between the fibers **210** and the substrate **230** in these embodiments. In other embodiments, the electrically-conductive fibers **210** are secured to a fabric **220** to form an embroidered fabric. The embroidered fabric may then be secured to the substrate **230**. In these embodiments, that assistant thread passes through the fabric layer **220** but need not pass through the substrate **230**.

[0040] The embroidered fabric may be secured to the partially cured substrate by contacting the embroidered fabric with a surface of the substrate followed by curing. In some embodiments, the side of the embroidered fabric which does not include electrically-conductive fibers is the side brought into contact with the substrate.

[0041] Electronic devices with multiple layers of electrically-conductive fibers may be fabricated by securing each electrically-conductive fiber-containing layer to a different substrate. The surfaces to be joined may be cleaned and contacted with an uncured or partially cured composition comprising the substrate materials followed by lamination and curing. Curing may be performed at a temperature of about 60° C. for about 3 hours. In some embodiments, contact between the electrically-conductive fibers and the uncured or partially cured composition is avoided to prevent increasing the resistance of the fibers.

[0042] Via holes **260** may be included to provide electrical paths between different circuit layers within and/or on surfaces of the substrate. The via holes may be created by piercing the substrate with sharp needles. Conductive elements may be guided through the holes to connect the circuit layers. In some embodiments, the conductive elements are electrically-conductive fibers. These elements may provide the additional benefit of further increasing the mechanical strength of the overall structure of the electronic device.

[0043] The fabric may comprise cotton, polyester, nylon, silk, composites thereof, or any other fabric materials.

[0044] The electrically-conductive fibers may include one or more threads having cores and conductive coatings or shells; yarns bundled with thin metal filaments; yarns or fabrics embedded with carbon nanotubes; and fabrics embedded with metal filaments. Fibers having polymeric cores and metallic shells are preferred due to their high mechanical strength and low material losses in radio frequency applications. In some embodiments, each thread has a diameter of

from about 7 to about 15 μm , including about 10 μm . Each fiber may include from about 50 to about 2,000 threads, including from about 150 to about 700 threads.

[0045] The core may comprise an aramid fiber or a polyoxazole. The aramid fibers may be para-aramid fibers such as the KEVLAR® fibers (commercially available from DuPont). The polyoxazole may be p-phenylene-2,6-benzobisoxazole (PBO) such as ZYLON® (commercially available from Toyobo). The core material imparts mechanical strength and flexibility to the threads. The core may have a diameter of from about 3 to about 10 μm , including about 7 μm .

[0046] The conductive shell may comprise a metal or carbon nanotubes. In some embodiments, the metal is selected from the group consisting of silver, copper, and nickel. The conductive shell imparts electrical conductivity to the threads. The conductive shell is preferably a uniform coating on the core and may have a thickness of from about 1 to about 3 μm .

[0047] A plurality of the threads may be bundled together to achieve a desired thickness for the electrically-conductive fiber and to enhance conductivity. The desired thickness may depend on the specific circuit component being fabricated. Each fiber may include from about 150 to about 700 threads. The fiber may have a thickness of from about 0.05 to about 0.50 millimeters.

[0048] The fabric or substrate may be embroidered with the electrically-conductive fibers at a stitching density greater than 30 stitches per cm^2 , including greater than 50 stitches per cm^2 and greater than 70 stitches per cm^2 . Increasing the stitching density increases the surface conductivity of the device since more conductive material is present per unit area.

[0049] The electrically-conductive layer may have a surface conductivity of from about 0.2 to about 0.5 $\text{m}\Omega/\square$, including from about 0.3 to about 0.4 $\text{m}\Omega/\square$.

[0050] In some embodiments, a second layer of electrically-conductive fiber(s) may be embroidered atop the first layer. This process may be referred to as double-layer embroidery and allows higher stitching density and thus conductivity to be achieved.

[0051] The assistant thread may comprise cotton, polyester, nylon, silk, or a composite thereof. In some embodiments, the assistant thread comprises the same type of material as the fabric.

[0052] The optional reinforcement layer **240** may be added to enhance the mechanical strength of the device. In some embodiments, the reinforcement layer may not extend through the entire substrate, such that the sections of the substrate to either side of the reinforcement layer are in physical contact with each other. For example, the reinforcement layer may have a grid configuration. The reinforcement layer may comprise an aramid fiber or a polyoxazole. In some embodiments, the reinforcement layer is woven into the substrate.

[0053] The ground plane **250** comprises a conductive material. The conductive material may be selected from the group consisting of carbon nanotubes, metals, and electrically-conductive fibers. In some embodiments, the metal is selected from the group consisting of silver, nickel, and copper. The ground plane may be in the form of a grid. In addition to serving an electrical function, the ground plane may also reinforce the device mechanically. The electrically-conductive fibers in the ground plane, in the via holes, and in the electrically-conductive fiber layer may be the same or different.

[0054] The manufacturing methods of the present disclosure may be performed manually and/or through an automated process. The automated process may include making or providing a design pattern in an embroidery design computer program; and realizing the design pattern on a fabric layer or substrate using a computerized sewing machine. The design pattern may be selected based on the desired properties for a particular application.

[0055] Aspects of the present disclosure may be further understood by referring to the following examples. The examples are illustrative, and are not intended to be limiting embodiments thereof.

Examples

[0056] AMBERSTRAND® fibers (commercially available from Syscom Advanced Materials), which include PBO cores and silver coatings, were utilized as the electrically-conductive fibers in the Examples. AMBERSTRAND® fibers exhibit high tensile strength, flexibility, and a very low resistivity of 0.8 Ω /m. These fibers possess high strength needed for load-bearing applications while maintaining high electrical conductivities at radio frequencies.

Substrate Formation and Single Layer Embroidered Fabric Attachment

[0057] SYLGARD® 184 (commercially available from Dow Corning), a silicone elastomer including a base and a curing agent, (commercially available from Dow Corning) was added to a high density polyethylene (HDPE) container at a weight ratio of 10:1 (50 g PDMS base and 5 g curing agent). The HDPE container had a smooth internal surface to minimize bubble formation.

[0058] The inner and outer caps of the container were closed and the container was weighed. The container was placed inside a vacuum mixer. The vacuum mixer was adjusted to the container's weight. The mixer was set to a rotation speed of from 1,500 to 2,000 rpm, a vacuum pressure of 10 kPa, and a mixing time of 100 to 120 seconds. The container was removed from the mixer after mixing. Four separate batches were prepared.

[0059] COG820MW was added to three of the four batches in varying amounts of 10 vol %, 20 vol %, and 30 vol %.

[0060] Each batch was tape-casted on a glass platform to form a thick substrate having smooth surfaces and a uniform thickness.

[0061] The casted substrate was partially cured at a temperature about 55° C. for about 10 minutes. The partially cured substrate had a tacky surface.

[0062] The backside of an embroidered fabric was cleaned using isopropanol and de-dusted with compressed air. The fabric was flattened in a hoop and clamped on a supporting frame. The backside of the fabric was oriented to face a top surface of the partially cured PDMS.

[0063] The clamp height was gradually adjusted to lower the hoop onto the PDMS surface. Due to its high viscosity, the PDMS adhered to the fabric without flowing over the conductive, embroidered portions.

[0064] The PDMS was cured for from about 2.5 to 3 hours at a temperature of about 100° C. The substrate was not tacky on its surface after curing was completed. The cured structure was removed from the mold or support.

[0065] FIG. 3 is a graph illustrating the dielectric constant for composite substrates including varying amounts of the ceramic material.

Electrically-Conductive Fiber Transmission Lines

[0066] Three devices with single layer 50 Ω transmission lines on substrates were fabricated. The substrates comprised PDMS with $\epsilon_r=3$. Device 1 included an electrically-conductive fiber conductor and an electrically-conductive fiber ground plane. Device 2 included an electrically-conductive fiber conductor and a copper ground plane. Device 3 included a copper conductor and a copper ground plane. The S-parameters of all three transmission lines were measured using a 2-port Agilent N5230 network analyzer at frequencies of 10 MHz to 4 GHz. The results are included in Table 1:

TABLE 1

Device Number	Conductor	Ground Plane	Max $ S_{21} $ (dB/cm)
1	Electrically-conductive fiber	Electrically-conductive fiber	0.21
2	Electrically-conductive fiber	Copper	0.17
3	Copper	Copper	0.14

[0067] Device 1 had a maximum insertion loss of 0.21 dB/cm at frequencies up to 4 GHz, 0.07 dB/cm higher than that of the all copper transmission line of Device 3. The corresponding insertion loss of Device 2 was 0.17 dB/cm, only 0.03 dB/cm greater than that of Device 3. Since the only difference between Devices 2 and 3 was the surface conductor material, it can be concluded that the electrically-conductive fiber and copper exhibit comparable performance. Without wishing to be bound by theory, it is believed that the insertion loss of Device 1 resulted from (1) impedance mismatch caused by parasitic reactance from silver epoxy paste at junctions; and (2) higher resistance of the electrically-conductive fiber ground plane. Overall, the measurements demonstrated that the embroidered electrically-conductive transmission lines exhibited good conductivity at radio frequencies.

[0068] A double layer device, Device 4, was fabricated by bringing together two PDMS substrates. Each substrate included an outer surface having an embroidered transmission line and an inner surface opposite the outer surface. The inner surfaces of the substrates were laminated together using a thin layer of fresh, i.e. uncured, PDMS in between. The fresh layer was cured in an oven or on a hot plate for about one hour. The two transmission lines were connected by a via hole. The via hole was created by pushing an electrically-conductive fiber through the PDMS using a needle. A silver epoxy was used to connect the electrically-conductive fiber in the via hole to the transmission lines. A control double layer device including a copper conductor and copper ground plane (Device 5) was also fabricated. The S-parameters of both devices were measured using a 2-port Agilent N5230 network analyzer at frequencies of 10 MHz to 4 GHz. The results are included in Table 2:

TABLE 2

Device Number	Conductor	Ground Plane	Max $ S_{21} $ (dB/cm)
4	Electrically-conductive fiber	Electrically-conductive fiber	0.34
5	Copper	Copper	0.14

[0069] The measured S_{21} of the electrically-conductive fiber transmission line had a maximum loss of 0.34 dB/cm at frequencies of up to 4 GHz, only 0.20 dB/cm higher than that of the copper transmission line. The higher S_{21} was primarily due to the imperfect via hole connection between the transmission lines and power loss on the ground plane.

[0070] Both the single- and double-layer transmission line structures exhibited satisfactory radiofrequency properties. Furthermore, both structures maintained these properties after repeated flexing.

Embroidered Patch

[0071] An embroidered patch comprising electrically-conductive fibers was fabricated and secured to a composite PDMS/RET substrate to form an antenna. The patch had a thickness of about 2 mm. The composite substrate comprised 10 vol % of RET, had an ϵ_r of 4.2, and exhibited a $\tan \delta < 0.01$. The patch was probe-fed at a specific location to achieve an impedance match to a 50 Ω coaxial cable. The probe was connected to the antenna using silver epoxy. When tested on a planar surface, the resonant frequency of the patch was 2.20 GHz which matched that of a simulated, perfectly electrical conducting (PEC) patch. The match indicated that the embroidered patch generated an effectively continuous conductive surface at UHF frequencies. The flat patch antenna exhibited a realized gain of 5.7 dB, only 0.2 dB less than that of the PEC patch. The performance of the antenna did not degrade after repetitive flexing.

[0072] To further evaluate radiofrequency performance, the antenna was mounted on a metal cylinder having a diameter of about 80 mm. The measured S_{11} and radiation patterns of the patch were similar to predictions based on an HFSS simulation. The realized gain was only 1 dB lower than simulated. Compared to the planar orientation, the curvilinear-oriented patch had a lower resonant frequency of 2.06 GHz and a reduced gain of 3.0 dB. The frequency change was due to a 13% elongation of the patch dimension in the H-plane cut. However, the gain reduction (compared to the PEC) was primarily caused by stretching the conductive patch and the resultant higher resistance of the patch's surface.

[0073] A summary of the results of the performance testing of the antenna comprising the patch is shown in Table 3:

TABLE 3

Conductor	Planar Surface		Curvilinear Surface	
	f_{resonant} (GHz)	Realized gain (dB)	f_{resonant} (GHz)	Realized gain (dB)
PEC	2.20	5.9	2.06	4.1
Electrically-conductive fiber	2.20	5.7	2.06	3.0

Embroidered Array

[0074] An antenna comprising a 4x1 electrically-conductive fiber array on a substrate was fabricated, analyzed on a planar surface, and compared to corresponding copper and PEC arrays on substrates. The composite substrate comprised 10 vol % of RET, had an ϵ_r of 4.2, and exhibited a $\tan \delta < 0.01$. The antenna had a resonance frequency of 2.31 GHz and a realized gain of 7.0 dB. The resonance frequency was com-

parable to that of the copper and PEC antennas. The slight difference was likely due to imperfect geometric accuracy of the fabricated array.

[0075] The antenna was also analyzed on a curvilinear surface by attachment to a cylinder. The realized gain of the electrically-conductive fiber array was 4.6 dB, only 1 dB less than that of the copper array. The increased spacing during bending led to the difference between the radiation patterns of the curvilinear and planar configurations of the antenna.

[0076] A summary of the results of the performance testing of the antenna comprising the array is shown in Table 4.

TABLE 4

Conductor	Planar Surface		Curvilinear Surface	
	f_{resonant} (GHz)	Realized gain (dB)	f_{resonant} (GHz)	Realized gain (dB)
PEC	2.34	7.8	2.33	5.7
Copper	2.34	7.6	2.33	5.4
Electrically-conductive fiber	2.31	7.0	2.33	4.6

[0077] The present disclosure has been described with reference to exemplary embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the present disclosure be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

1. A method for manufacturing a conformal electronic device, comprising:

providing an electrically-conductive fiber in proximity to a first surface of a substrate; and

sewing an assistant thread through the first surface, around the electrically conductive-fiber, and back through the first surface to secure the electrically-conductive fiber to the substrate.

2. The method of claim 1, wherein the substrate comprises a silicon-based polymer.

3. The method of claim 2, wherein the silicon-based polymer is a polysiloxane or a polysilsesquioxane.

4. The method of claim 3, wherein the polysiloxane is polydimethylsiloxane.

5. The method of claim 2, wherein the substrate further comprises a ceramic material dispersed in the silicon-based polymer.

6. The method of claim 5, wherein the ceramic material comprises a titanate.

7. The method of claim 6, wherein the titanate is a rare earth titanate.

8. The method of claim 1, wherein the electrically-conductive fiber comprises one or more electrically-conductive threads; and wherein each of said one or more electrically-conductive threads comprises a core and a conductive shell.

9. The method of claim 8, wherein the conductive shell comprises a conductive material selected from the group consisting of carbon nanotubes and metals.

10. The method of claim 9, wherein the metal is selected from the group consisting of silver, copper, and nickel.

11. The method of claim 8, wherein the core comprises an aramid fiber or an oxazole.

12. The method of claim 1, wherein the sewing is performed in a predetermined pattern using a digitized sewing machine.

13. The method of claim **1**, wherein the substrate is pre-stretched prior to sewing.

14. The method of claim **1**, wherein the conformal electronic device further comprises a fabric layer between the substrate and the electrically-conductive fiber.

15. A method for manufacturing a conformal electronic device, comprising:

providing an electrically-conductive fiber in proximity to a first surface of a fabric; and

sewing an assistant thread through the first surface, around the electrically conductive-fiber, and back through the first surface to secure the electrically-conductive fiber to the fabric to form an embroidered fabric.

16. The method of claim **15**, further comprising:

securing the embroidered fabric to a substrate.

17. The method of claim **16**, wherein the substrate comprises a silicon-based polymer matrix and a ceramic material dispersed within the silicon-based polymer matrix.

18. The method of claim **15**, wherein the electrically-conductive fiber comprises one or more electrically-conductive threads; and wherein each of the one or more electrically-conductive threads comprises a core and an electrically-conductive shell.

19. The method of claim **18**, wherein the electrically-conductive shell comprises a conductive material selected from the group consisting of carbon nanotubes and metals.

20. A method for manufacturing a conformal electronic device, comprising:

providing a predetermined digital pattern to a sewing machine; and

embroidering the pattern onto a first surface of a substrate with an electrically-conductive fiber using an assistant thread from the sewing machine;

wherein the embroidering is performed by

(a) providing a portion of the electrically-conductive fiber in proximity to a pattern section of the first surface of the substrate;

(b) sewing the assistant thread from a second surface of the substrate through the first surface, around the portion of the electrically-conductive fiber, and back through the first surface to secure the portion of the electrically-conductive fiber to the pattern section of the substrate; and

(c) repeating elements (a) and (b) for different portions of the electrically-conductive fiber and different pattern sections of the first surface of the substrate until the pattern is complete.

* * * * *