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(54) **Title:** COPPER-CLAD LAMINATE AND METHOD OF FORMING THE SAME

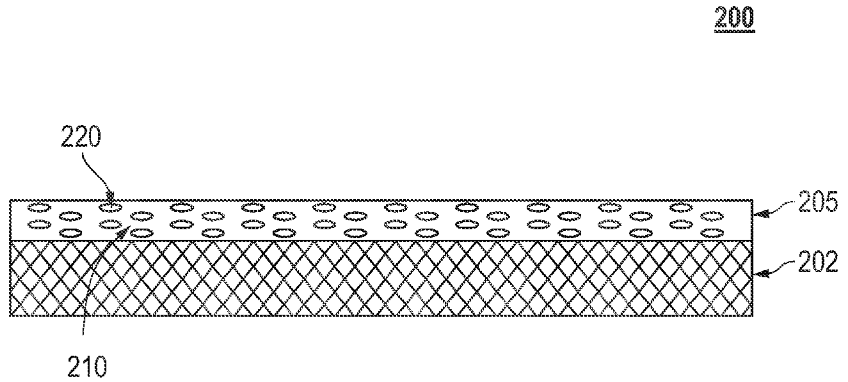

FIG. 2

(57) **Abstract:** The present disclosure relates to a copper-clad laminate that may include a copper foil layer and a dielectric coating overlying the copper foil layer. The dielectric coating may include a resin matrix component, and a ceramic filler component. The ceramic filler component may include a first filler material. The dielectric coating may have an average thickness of not greater than about 20 microns.

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COPPER-CLAD LAMINATE AND METHOD OF FORMING THE SAME

TECHNICAL FIELD

The present disclosure relates to a copper-clad laminate and methods of forming the same. In particular, the present disclosure related to a copper-clad laminate with a dielectric coating and methods of forming the same.

BACKGROUND ART

Copper-clad laminates (CCLs) include a dielectric material laminated onto or between two layers of conductive copper foil. Subsequent operations transform such CCLs into printed circuit boards (PCBs). When used to form PCBs, the conductive copper foil is selectively etched to form circuitry with through holes that are drilled between layers and metalized, i.e. plated, to establish conductivity between layers in multilayer PCBs. CCLs must therefore exhibit excellence thermomechanical stability. PCBs are also routinely exposed to excessively high temperatures during manufacturing operations, such as soldering, as well as in service. So, they must function at continuous temperatures above 200°C without deforming and withstand dramatic temperature fluctuations while resisting moisture absorption. The dielectric layer of a CCL serves as a spacer between the conductive layers and can minimize electrical signal loss and crosstalk by blocking electrical conductivity. The lower the dielectric constant (permittivity) of the dielectric layer, the higher the speed of the electrical signal through the layer. A low dissipation factor, which is dependent upon temperature and frequency, as well as the polarizability of the material, is therefore very critical for high-frequency applications. Accordingly, improved dielectric materials and dielectric layers that can be used in PCBs and other high-frequency applications are desired.

SUMMARY

According to a first aspect, a copper-clad laminate may include a copper foil layer and a dielectric coating overlying the copper foil layer. The dielectric coating may include a resin matrix component, and a ceramic filler component. The ceramic filler component may include a first filler material. The dielectric coating may have an average thickness of not greater than about 20 microns.

According to another aspect, a copper-clad laminate may include a copper foil layer and a dielectric coating overlying the copper foil layer. The dielectric coating may include a resin matrix component, and a ceramic filler component. The ceramic filler component may include a first filler material. The particle size distribution of the first filler material may have a D_{10} of at least about 0.2 microns and not greater than about 1.6, a D_{50} of at least about 0.5

microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

According to yet another aspect, a copper-clad laminate may include a copper foil layer and a dielectric coating overlying the copper foil layer. The dielectric coating may include a resin matrix component, and a ceramic filler component. The ceramic filler component may include a first filler material. The first filler material may further have a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

According to another aspect, a printed circuit board may include a copper-clad laminate. The copper-clad laminate may include a copper foil layer and a dielectric coating overlying the copper foil layer. The dielectric coating may include a resin matrix component, and a ceramic filler component. The ceramic filler component may include a first filler material. The dielectric coating may have an average thickness of not greater than about 20 microns.

According to still another aspect, a printed circuit board may include a copper-clad laminate. The copper-clad laminate may include a copper foil layer and a dielectric coating overlying the copper foil layer. The dielectric coating may include a resin matrix component, and a ceramic filler component. The ceramic filler component may include a first filler material. The particle size distribution of the first filler material may have a D_{10} of at least about 0.2 microns and not greater than about 1.6, a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

According to another aspect, a printed circuit board may include a copper-clad laminate. The copper-clad laminate may include a copper foil layer and a dielectric coating overlying the copper foil layer. The dielectric coating may include a resin matrix component, and a ceramic filler component. The ceramic filler component may include a first filler material. The first filler material may further have a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

According to another aspect, a method of forming a copper-clad laminate may include providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, and forming the forming mixture into a dielectric coating overlying the copper foil. The ceramic filler precursor component may include a first filler precursor material. The dielectric coating may have an average thickness of not greater than about 20 microns.

According to yet another aspect, a method of forming a copper-clad laminate may include providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, and forming the forming mixture into a dielectric coating overlying the copper foil. The ceramic filler precursor component may include a first filler precursor material. The particle size distribution of the first filler material may have a D_{10} of at least about 0.2 microns and not greater than about 1.6, a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

According to another aspect, a method of forming a copper-clad laminate may include providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, and forming the forming mixture into a dielectric coating overlying the copper foil. The ceramic filler precursor component may include a first filler precursor material. The first filler precursor material may further have a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler precursor material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler precursor material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler precursor material.

According to another aspect, a method of forming a printed circuit board may include providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, and forming the forming mixture into a dielectric coating overlying the copper foil. The ceramic filler precursor component may include a first filler precursor material. The dielectric coating may have an average thickness of not greater than about 20 microns.

According to yet another aspect, a method of forming a printed circuit board may include providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, and forming the forming mixture into a dielectric coating overlying the copper foil. The ceramic filler precursor component may include a first filler precursor material. The particle size distribution of the first filler material may have a D_{10} of at least about 0.2 microns and not greater than about 1.6, a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

According to another aspect, a method of forming a printed circuit board may include providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, and forming the forming mixture into a dielectric coating overlying the copper foil. The ceramic filler precursor component may include a first filler precursor material. The first filler precursor material may further have a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler precursor material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler precursor material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler precursor material.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments are illustrated by way of example and are not limited to the accompanying figures.

FIG. 1 includes a diagram showing a copper-clad laminate forming method according to embodiments described herein;

FIG. 2 includes an illustration showing the configuration of a copper-clad laminate formed according to embodiments described herein;

FIG. 3 includes a diagram showing a printed circuit board forming method according to embodiments described herein; and

FIG. 4 includes an illustration showing the configuration of a printed circuit board formed according to embodiments described herein.

Skilled artisans appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS(S)

The following discussion will focus on specific implementations and embodiments of the teachings. The detailed description is provided to assist in describing certain embodiments and should not be interpreted as a limitation on the scope or applicability of the disclosure or teachings. It will be appreciated that other embodiments can be used based on the disclosure and teachings as provided herein.

The terms “comprises,” “comprising,” “includes,” “including,” “has,” “having” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a method, article, or apparatus that comprises a list of features is not necessarily limited only to those features but may include other features not expressly listed or inherent to such method, article, or apparatus. Further, unless expressly stated to the contrary, “or” refers to an inclusive-or and not to an exclusive-or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

Embodiments described herein are generally directed to a copper-clad laminates that may include a copper foil layer and a dielectric coating overlying the copper foil layer. According to certain embodiments, the dielectric coating may include a resin matrix component, and a ceramic filler component.

Referring first to a method of forming a copper-clad laminate, FIG. 1 includes a diagram showing a forming method 100 for forming a copper-clad laminate according to embodiments described herein. According to particular embodiments, the forming method 100 may include a first step 110 of providing a copper foil layer, a second step 120 of combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, and a third step 130 of forming the forming mixture into a dielectric coating overlying the copper foil layer to form the copper-clad laminate.

According to particular embodiments, the ceramic filler precursor component may include a first filler precursor material, which may have particular characteristics that may improve performance of the copper-clad laminate formed by the forming method 100.

According to certain embodiments, the first filler precursor material may have a particular size distribution. For purposes of embodiments described herein, the particle size distribution of a material, for example, the particle size distribution of a first filler precursor material may be described using any combination of particle size distribution D-values D_{10}, D_{50} and D_{90}. The D_{10} value from a particle size distribution is defined as a particle size value where 10% of the particles are smaller than the value and 90% of the particles are larger than the value. The D_{50} value from a particle size distribution is defined as a particle size value where 50% of the particles are smaller than the value and 50% of the particles are larger than the value. The D_{90} value from a particle size distribution is defined as a particle size value where 90% of the particles are smaller than the value and 10% of the particles are larger than the value. For purposes of embodiments described herein, particle size measurements for a particular material are made using laser diffraction spectroscopy.

According to certain embodiments, the first filler precursor material may have a particular size distribution D_{10} value. For example, the D_{10} of the first filler precursor material may be at least about 0.2 microns, such as, at least about 0.3 microns or at least about 0.4 microns or at least about 0.5 microns or at least about 0.6 microns or at least about 0.7 microns or at least about 0.8 microns or at least about 0.9 microns or at least about 1.0 microns or at least about 1.1 microns or even at least about 1.2 microns. According to still other embodiments, the D_{10} of the first filler material may be not greater than about 1.6 microns, such as, not greater than about 1.5 microns or even not greater than about 1.4 microns. It will be appreciated that the D_{10} of the first filler precursor material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the D_{10} of the first filler precursor material may be within a range between, and including, any of the minimum and maximum values noted above.

According to other embodiments, the first filler precursor material may have a particular size distribution D_{50} value. For example, the D_{50} of the first filler precursor material may be at least about 0.5 microns, such as, at least about 0.6 microns or at least about 0.7 microns or at least about 0.8 microns or at least about 0.9 microns or at least about 1.0 microns or at least about 1.1 microns or at least about 1.2 microns or at least about 1.3 microns or at least about 1.4 microns or at least about 1.5 microns or at least about 1.6 microns or at least about 1.7 microns or at least about 1.8 microns or at least about 1.9 microns or at least about 2.0 microns or at least about 2.1 microns or even at least about 2.2 microns. According to still other embodiments, the D_{50} of the first filler material may be not greater than about 2.7 microns, such as, not greater than about 2.6 microns or not greater than about 2.5 microns or even not greater than about 2.4 microns. It will be appreciated that the D_{50} of the first filler precursor material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the D_{50} of the first filler precursor material may be within a range between, and including, any of the minimum and maximum values noted above.

According to other embodiments, the first filler precursor material may have a particular size distribution D_{90} value. For example, the D_{90} of the first filler precursor material may be at least about 0.8 microns, such as, at least about 0.9 microns or at least about 1.0 microns or at least about 1.1 microns or at least about 1.2 microns or at least about 1.3 microns or at least about 1.4 microns or at least about 1.5 microns or at least about 1.6 microns or at least about 1.7 microns or at least about 1.8 microns or at least about 1.9 microns or at least about 2.0 microns or at least about 2.1 microns or at least about 2.2 microns or at least about 2.3 microns or at least about 2.4 microns or at least about 2.5 microns or at least about 2.6 microns or even at least about 2.7 microns. According to still other embodiments, the D_{90} of the first filler material may be not greater than about 8.0 microns, such as, not greater than about 7.5 microns or not greater than about 7.0 microns or not greater than about 6.5 microns or not greater than about 6.0 microns or not greater than about 5.5 microns or not greater than about 5.4 microns or not greater than about 5.3 microns or not greater than about 5.2 microns or even not greater than about 5.1 microns. It will be appreciated that the D_{90} of the first filler precursor material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the D_{90} of the first filler precursor material may be within a range between, and including, any of the minimum and maximum values noted above.

According to still other embodiments, the first filler precursor material may have a particular mean particle size as measured using laser diffraction spectroscopy. For example, the mean particle size of the first filler precursor material may be not greater than about 10 microns, such as, not greater than about 9 microns or not greater than about 8 microns or not greater than about 7 microns or not greater than about 6 microns or not greater than about 5 microns or not greater than about 4 microns or not greater than about 3 microns or even not greater than about 2 microns. It will be appreciated that the mean particle size of the first filler precursor material may be any value between, and including, any of the values noted above. It will be further appreciated that the mean particle size of the first filler precursor material may be within a range between, and including, any of the values noted above.

According to still other embodiments, the first filler precursor material may be described as having a particular particle size distribution span (PSDS), where the PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler precursor material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler precursor material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler precursor material. For example, the PSDS of the first filler precursor material may be not greater than about 5, such as, not greater than about 4.5 or not greater than about 4.0 or not greater than about 3.5 or not greater than about 3.0 or even not greater than about 2.5. It will be appreciated that the PSDS of the first filler precursor material may be any value between, and including, any of the values noted above. It will be further appreciated that the PSDS of the first filler precursor material may be within a range between, and including, any of the values noted above.

According to still other embodiments, the first filler precursor material may be described as having a particular average surface area as measured using Brunauer-Emmett-Teller (BET) surface area analysis (Nitrogen Adsorption). For example, the first filler precursor material may have an average surface area of not greater than about 10 m^2/g, such as, not greater than about 9.9 m^2/g or not greater than about 9.5 m^2/g or not greater than about 9.0 m^2/g or not greater than about 8.5 m^2/g or not greater than about 8.0 m^2/g or not greater than about 7.5 m^2/g or not greater than about 7.0 m^2/g or not greater than about 6.5 m^2/g or not greater than about 6.0 m^2/g or not greater than about 5.5 m^2/g or not greater than about 5.0 m^2/g or not greater than about 4.5 m^2/g or not greater than about 4.0 m^2/g or even not greater than about 3.5 m^2/g. According to still other embodiments, the first filler precursor material may have an average surface area of at least about 1.2 m^2/g, such as, at least about 2.2 m^2/g. It will be appreciated that the average surface area of the first filler precursor material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the average surface area of the first filler precursor material may be within a range between, and including, any of the minimum and maximum values noted above.

According to other embodiments, the first filler precursor material may include a particular material. According to particular embodiments, the first filler precursor material may include a silica based compound. According to still other embodiments, the first filler precursor material may consist of a silica based compound. According to other embodiments, the first filler precursor material may include silica. According to still other embodiments, the first filler precursor material may consist of silica.

According to yet other embodiments, the forming mixture may include a particular content of the ceramic filler precursor component. For example, the content of the ceramic filler precursor component may be at least about 30 vol.% for a total volume of the first forming mixture, such as, at least about 31 vol.% or at least about 32 vol.% or at least about 33 vol.% or at least about 34 vol.% or at least about 35 vol.% or at least about 36 vol.% or at least about 37 vol.% or at least about 38 vol.% or at least about 39 vol.% or at least about 40 vol.% or at least about 41 vol.% or at least about 42 vol.% or at least about 43 vol.% or at least about 44 vol.% or at least about 45 vol.% or at least about 46 vol.% or at least about 47 vol.% or at least about 48 vol.% or at least about 49 vol.% or at least about 50 vol.% or at least about 51 vol.% or at least about 52 vol.% or at least about 53 vol.% or even at least about 54 vol.%. According to still other embodiments, the content of the ceramic filler precursor component may be not greater than about 57 vol.% for a total volume of the forming mixture, such as, not greater than about 56 vol.% or even not greater than about 55 vol.%. It will be appreciated that the content of the ceramic filler precursor component may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the ceramic filler precursor component may be within a range between, and including, any of the minimum and maximum values noted above.

According to still other embodiments, the ceramic filler precursor component may include a particular content of the first filler precursor material. For example, the content of the first filler precursor material may be at least about 80 vol.% for a total volume of the ceramic filler precursor component, such as, at least about 81 vol.% or at least about 82 vol.% or at least about 83 vol.% or at least about 84 vol.% or at least about 85 vol.% or at least about 86 vol.% or at least about 87 vol.% or at least about 88 vol.% or at least about 89 vol.% or even at least about 90 vol.%. According to still other embodiments, the content of the first filler precursor material may be not greater than about 100 vol.% for a total volume of the ceramic filler precursor component, such as, not greater than about 99 vol.% or not greater than about 98 vol.% or not greater than about 97 vol.% or not greater than about 96 vol.% or not greater than about 95 vol.% or not greater than about 94 vol.% or not greater than about 93 vol.% or even not greater than about 92 vol.%. It will be appreciated that the content of the first filler precursor material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the first filler precursor material may be within a range between, and including, any of the minimum and maximum values noted above.

According to still other embodiments, the ceramic filler precursor component may include a second filler precursor material.

According to yet other embodiments, the second filler precursor material may include a particular material. For example, the second filler precursor material may include a high dielectric constant ceramic material, such as, a ceramic material having a dielectric constant of at least about 14. According to particular embodiments, the second filler precursor material may include any high dielectric constant ceramic material, such as, TiO_2, $SrTiO_3$, $ZrTi_2O_6$, $MgTiO_3$, $CaTiO_3$, $BaTiO_4$ or any combination thereof.

According to yet other embodiments, the second filler precursor material may include TiO_2. According to still other embodiments, the second filler precursor material may consist of TiO_2.

According to still other embodiments, the ceramic filler precursor component may include a particular content of the second filler precursor material. For example, the content of the second filler precursor material may be at least about 1 vol.% for a total volume of the ceramic filler precursor component, such as, at least about 2 vol.% or at least about 3 vol.% or at least about 4 vol.% or at least about 5 vol.% or at least about 6 vol.% or at least about 7 vol.% or at least about 8 vol.% or at least about 9 vol.% or at least about 10 vol.%. According to still other embodiments, the content of the second filler precursor material may be not greater than about 20 vol.% for a total volume of the ceramic filler precursor component, such as, not greater than about 19 vol.% or not greater than about 18 vol.% or not greater than about 17 vol.% or not greater than about 16 vol.% or not greater than about 15 vol.% or not greater than about 14 vol.% or not greater than about 13 vol.% or not greater than about 12 vol.%. It will be appreciated that the content of the second filler precursor material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the second filler precursor material may be within a range between, and including, any of the minimum and maximum values noted above.

According to yet other embodiments, the ceramic filler precursor component may include a particular content of amorphous material. For example, the ceramic filler precursor component may include at least about 97% amorphous material, such as, at least about 98% or even at least about 99%. It will be appreciated that the content of amorphous material may be any value between, and including, any of the values noted above. It will be further appreciated that the content of the content of amorphous material may be within a range between, and including, any of the values noted above.

According to other embodiments, the resin matrix precursor component may include a particular material. For example, the resin matrix precursor component may include a perfluoropolymer. According to still other embodiments, the resin matrix precursor component may consist of a perfluoropolymer.

According to yet other embodiments, the perfluoropolymer of the resin matrix precursor component may include a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof. According to other embodiments, the perfluoropolymer of the resin matrix precursor component may consist of a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof.

According to yet other embodiments, the perfluoropolymer of the resin matrix precursor component may include polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof. According to still other embodiments, the perfluoropolymer of the resin matrix precursor component may consist of polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

According to yet other embodiments, the forming mixture may include a particular content of the resin matrix precursor component. For example, the content of the resin matrix precursor component may be at least about 45 vol.% for a total volume of the forming mixture, such as, at least about 46 vol.% or at least about 47 vol.% or at least about 48 vol.% or at least about 49 vol.% or at least about 50 vol.% or at least about 51 vol.% or at least about 52 vol.% or at least about 53 vol.% or at least about 54 vol.% or even at least about 55 vol.%. According to still other embodiments, the content of the resin matrix precursor component is not greater than about 63 vol.% for a total volume of the forming mixture or not greater than about 62 vol.% or not greater than about 61 vol.% or not greater than about 60 vol.% or not greater than about 59 vol.% or not greater than about 58 vol.% or even not greater than about 57 vol.%. It will be appreciated that the content of the resin matrix precursor component may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the resin matrix precursor component may be within a range between, and including, any of the minimum and maximum values noted above.

According to yet other embodiments, the forming mixture may include a particular content of the perfluoropolymer. For example, the content of the perfluoropolymer may be at least about 45 vol.% for a total volume of the forming mixture, such as, at least about 46 vol.% or at least about 47 vol.% or at least about 48 vol.% or at least about 49 vol.% or at least about 50 vol.% or at least about 51 vol.% or at least about 52 vol.% or at least about 53 vol.% or at least about 54 vol.% or even at least about 55 vol.%. According to still other embodiments, the content of the perfluoropolymer may be not greater than about 63 vol.% for a total volume of the forming mixture, such as, not greater than about 62 vol.% or not greater than about 61 vol.% or not greater than about 60 vol.% or not greater than about 59 vol.% or not greater than about 58 vol.% or even not greater than about 57 vol.%. It will be appreciated that the content of the perfluoropolymer may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the perfluoropolymer may be within a range between, and including, any of the minimum and maximum values noted above.

Referring now to embodiments of the copper-clad laminate formed according to forming method 100, FIG. 2 includes diagram of a copper-clad lamination 200. As shown in FIG. 2, the copper-clad laminate 200 may include a copper foil layer 202, and a dielectric coating 205 overlying a surface of the copper foil layer 202. According to certain embodiments, the dielectric coating 205 may include a resin matrix component 210 and a ceramic filler component 220.

According to particular embodiments, the ceramic filler component 220 may include a first filler material, which may have particular characteristics that may improve performance of the copper-clad laminate 200.

According to certain embodiments, the first filler material of the ceramic filler component 220 may have a particular size distribution. For purposes of embodiments described herein, the particle size distribution of a material, for example, the particle size distribution of a first filler material may be described using any combination of particle size distribution D-values D_{10}, D_{50} and D_{90}. The D_{10} value from a particle size distribution is defined as a particle size value where 10% of the particles are smaller than the value and 90% of the particles are larger than the value. The D_{50} value from a particle size distribution is defined as a particle size value where 50% of the particles are smaller than the value and 50% of the particles are larger than the value. The D_{90} value from a particle size distribution is defined as a particle size value where 90% of the particles are smaller than the value and 10% of the particles are larger than the value. For purposes of embodiments described herein, particle size measurements for a particular material are made using laser diffraction spectroscopy.

According to certain embodiments, the first filler material of the ceramic filler component 220 may have a particular size distribution D_{10} value. For example, the D_{10} of the first filler material may be at least about 0.2 microns, such as, at least about 0.3 microns or at least about 0.4 microns or at least about 0.5 microns or at least about 0.6 microns or at least about 0.7 microns or at least about 0.8 microns or at least about 0.9 microns or at least about 1.0 microns or at least about 1.1 microns or even at least about 1.2 microns. According to still other embodiments, the D_{10} of the first filler material may be not greater than about 1.6 microns, such as, not greater than about 1.5 microns or even not greater than about 1.4 microns. It will be appreciated that the D_{10} of the first filler material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the D_{10} of the first filler material may be within a range between, and including, any of the minimum and maximum values noted above.

According to other embodiments, the first filler material of the ceramic filler component 420 may have a particular size distribution D_{50} value. For example, the D_{50} of the first filler material may be at least about 0.5 microns, such as, at least about 0.6 microns or at least about 0.7 microns or at least about 0.8 microns or at least about 0.9 microns or at least about 1.0 microns or at least about 1.1 microns or at least about 1.2 microns or at least about 1.3 microns or at least about 1.4 microns or at least about 1.5 microns or at least about 1.6 microns or at least about 1.7 microns or at least about 1.8 microns or at least about 1.9 microns or at least about 2.0 microns or at least about 2.1 microns or even at least about 2.2 microns. According to still other embodiments, the D_{50} of the first filler material may be not greater than about 2.7 microns, such as, not greater than about 2.6 microns or not greater than about 2.5 microns or even not greater than about 2.4 microns. It will be appreciated that the D_{50} of the first filler material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the D_{50} of the first filler material may be within a range between, and including, any of the minimum and maximum values noted above.

According to other embodiments, the first filler material of the ceramic filler component 420 may have a particular size distribution D_{90} value. For example, the D_{90} of the first filler material may be at least about 0.8 microns, such as, at least about 0.9 microns or at least about 1.0 microns or at least about 1.1 microns or at least about 1.2 microns or at least about 1.3 microns or at least about 1.4 microns or at least about 1.5 microns or at least about 1.6 microns or at least about 1.7 microns or at least about 1.8 microns or at least about 1.9 microns or at least about 2.0 microns or at least about 2.1 microns or at least about 2.2 microns or at least about 2.3 microns or at least about 2.4 microns or at least about 2.5 microns or at least about 2.6 microns or even at least about 2.7 microns. According to still other embodiments, the D_{90} of the first filler material may be not greater than about 8.0 microns, such as, not greater than about 7.5 microns or not greater than about 7.0 microns or not greater than about 6.5 microns or not greater than about 6.0 microns or not greater than about 5.5 microns or not greater than about 5.4 microns or not greater than about 5.3 microns or not greater than about 5.2 microns or even not greater than about 5.1 microns. It will be appreciated that the D_{90} of the first filler material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the D_{90} of the first filler material may be within a range between, and including, any of the minimum and maximum values noted above.

According to still other embodiments, the first filler material of the ceramic filler component 220 may have a particular mean particle size as measured using laser diffraction spectroscopy. For example, the mean particle size of the first filler material may be not greater than about 10 microns, such as, not greater than about 9 microns or not greater than about 8 microns or not greater than about 7 microns or not greater than about 6 microns or not greater than about 5 microns or not greater than about 4 microns or not greater than about 3 microns or even not greater than about 2 microns. It will be appreciated that the mean particle size of the first filler material may be any value between, and including, any of the values noted above. It will be further appreciated that the mean particle size of the first filler material may be within a range between, and including, any of the values noted above.

According to still other embodiments, the first filler material of the ceramic filler component 220 may be described as having a particular particle size distribution span (PSDS), where the PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material. For example, the PSDS of the first filler material may be not greater than about 5, such as, not greater than about 4.5 or not greater than about 4.0 or not greater than about 3.5 or not greater than about 3.0 or even not greater than about 2.5. It will be appreciated that the PSDS of the first filler material may be any value between, and including, any of the values noted above. It will be further appreciated that the PSDS of the first filler material may be within a range between, and including, any of the values noted above.

According to still other embodiments, the first filler material of the ceramic filler component 220 may be described as having a particular average surface area as measured using Brunauer-Emmett-Teller (BET) surface area analysis (Nitrogen Adsorption). For example, the first filler material may have an average surface area of not greater than about 10 m^2/g, such as, not greater than about 9.9 m^2/g or not greater than about 9.5 m^2/g or not greater than about 9.0 m^2/g or not greater than about 8.5 m^2/g or not greater than about 8.0 m^2/g m^2/g or not greater than about 7.5 m^2/g or not greater than about 7.0 m^2/g or not greater than about 6.5 m^2/g or not greater than about 6.0 m^2/g or not greater than about 5.5 m^2/g or not greater than about 5.0 m^2/g or not greater than about 4.5 m^2/g or not greater than about 4.0 m^2/g or even not greater than about 3.5 m^2/g. According to still other embodiments, the first filler material may have an average surface area of at least about 1.2 m^2/g, such as, at least about 2.2 m^2/g. It will be appreciated that the average surface area of the first filler material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the average surface area of the first filler material may be within a range between, and including, any of the minimum and maximum values noted above.

According to other embodiments, the first filler material of the ceramic filler component 220 may include a particular material. According to particular embodiments, the first filler material may include a silica based compound. According to still other embodiments, the first filler material may consist of a silica based compound. According to other embodiments, the first filler material may include silica. According to still other embodiments, the first filler material may consist of silica.

According to yet other embodiments, the dielectric coating 205 may include a particular content of the ceramic filler component 220. For example, the content of the ceramic filler component 220 may be at least about 30 vol.% for a total volume of the dielectric coating 205, such as, at least about 31 vol.% or at least about 32 vol.% or at least about 33 vol.% or at least about 34 vol.% or at least about 35 vol.% or at least about 36 vol.% or at least about 37 vol.% or at least about 38 vol.% or at least about 39 vol.% or at least about 40 vol.% or at least about 41 vol.% or at least about 42 vol.% or at least about 43 vol.% or at least about 44 vol.% or at least about 45 vol.% or at least about 46 vol.% or at least about 47 vol.% or at least about 48 vol.% or at least about 49 vol.% or at least about 50 vol.% or at least about 51 vol.% or at least about 52 vol.% or at least about 53 vol.% or even at least about 54 vol.%. According to still other embodiments, the content of the ceramic filler component 420 may be not greater than about 57 vol.% for a total volume of the dielectric coating 400, such as, not greater than about 56 vol.% or even not greater than about 55 vol.%. It will be appreciated that the content of the ceramic filler component 220 may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the ceramic filler component 220 may be within a range between, and including, any of the minimum and maximum values noted above.

According to still other embodiments, the ceramic filler component 220 may include a particular content of the first filler material. For example, the content of the first filler material may be at least about 80 vol.% for a total volume of the ceramic filler component 220, such as, at least about 81 vol.% or at least about 82 vol.% or at least about 83 vol.% or at least about 84 vol.% or at least about 85 vol.% or at least about 86 vol.% or at least about 87 vol.% or at least about 88 vol.% or at least about 89 vol.% or even at least about 90 vol.%. According to still other embodiments, the content of the first filler material may be not greater than about 100 vol.% for a total volume of the ceramic filler component 220, such as, not greater than about 99 vol.% or not greater than about 98 vol.% or not greater than about 97 vol.% or not greater than about 96 vol.% or not greater than about 95 vol.% or not greater than about 94 vol.% or not greater than about 93 vol.% or even not greater than about 92 vol.%. It will be appreciated that the content of the first filler material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the first filler material may be within a range between, and including, any of the minimum and maximum values noted above.

According to still other embodiments, the ceramic filler component 220 may include a second filler material.

According to yet other embodiments, the second filler material of the ceramic filler component 220 may include a particular material. For example, the second filler material may include a high dielectric constant ceramic material, such as, a ceramic material having a dielectric constant of at least about 14. According to particular embodiments, the second filler material of the ceramic filler component 220 may include any high dielectric constant ceramic material, such as, TiO_2, $SrTiO_3$, $ZrTi_2O_6$, $MgTiO_3$, $CaTiO_3$, $BaTiO_4$ or any combination thereof.

According to yet other embodiments, the second filler material of the ceramic filler component 220 may include TiO_2. According to still other embodiments, the second filler material may consist of TiO_2.

According to still other embodiments, the ceramic filler component 220 may include a particular content of the second filler material. For example, the content of the second filler material may be at least about 1 vol.% for a total volume of the ceramic filler component 220, such as, at least about 2 vol.% or at least about 3 vol.% or at least about 4 vol.% or at least about 5 vol.% or at least about 6 vol.% or at least about 7 vol.% or at least about 8 vol.% or at least about 9 vol.% or at least about 10 vol.%. According to still other embodiments, the content of the second filler material may be not greater than about 20 vol.% for a total volume of the ceramic filler component 220, such as, not greater than about 19 vol.% or not greater than about 18 vol.% or not greater than about 17 vol.% or not greater than about 16 vol.% or not greater than about 15 vol.% or not greater than about 14 vol.% or not greater than about 13 vol.% or not greater than about 12 vol.%. It will be appreciated that the content of the second filler material may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the second filler material may be within a range between, and including, any of the minimum and maximum values noted above.

According to yet other embodiments, the ceramic filler component 220 may include a particular content of amorphous material. For example, the ceramic filler component 220 may include at least about 97% amorphous material, such as, at least about 98% or even at least about 99%. It will be appreciated that the content of amorphous material may be any value between, and including, any of the values noted above. It will be further appreciated that the content of the content of amorphous material may be within a range between, and including, any of the values noted above.

According to other embodiments, the resin matrix component 210 may include a particular material. For example, the resin matrix component 210 may include a perfluoropolymer. According to still other embodiments, the resin matrix component 410 may consist of a perfluoropolymer.

According to yet other embodiments, the perfluoropolymer of the resin matrix component 410 may include a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof. According to other embodiments, the perfluoropolymer of the resin matrix component 410 may consist of a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof.

According to yet other embodiments, the perfluoropolymer of the resin matrix component 410 may include polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof. According to still other embodiments, the perfluoropolymer of the resin matrix component 410 may consist of polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

According to yet other embodiments, the dielectric coating 200 may include a particular content of the resin matrix component 210. For example, the content of the resin matrix component 210 may be at least about 50 vol.% for a total volume of the dielectric coating 200, such as, at least about 51 vol.% or at least about 52 vol.% or at least about 53 vol.% or at least about 54 vol.% or even at least about 55 vol.%. According to still other embodiments, the content of the resin matrix component 210 is not greater than about 63 vol.% for a total volume of the dielectric coating 200 or not greater than about 62 vol.% or not greater than about 61 vol.% or not greater than about 60 vol.% or not greater than about 59 vol.% or not greater than about 58 vol.% or even not greater than about 57 vol.%. It will be appreciated that the content of the resin matrix component 210 may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the resin matrix component 210 may be within a range between, and including, any of the minimum and maximum values noted above.

According to yet other embodiments, the dielectric coating 205 may include a particular content of the perfluoropolymer. For example, the content of the perfluoropolymer may be at least about 50 vol.% for a total volume of the dielectric coating 405, such as, at least about 51 vol.% or at least about 52 vol.% or at least about 53 vol.% or at least about 54 vol.% or even at least about 55 vol.%. According to still other embodiments, the content of the perfluoropolymer may be not greater than about 63 vol.% for a total volume of the dielectric coating 200, such as, not greater than about 62 vol.% or not greater than about 61 vol.% or not greater than about 60 vol.% or not greater than about 59 vol.% or not greater than about 58 vol.% or even not greater than about 57 vol.%. It will be appreciated that the content of the perfluoropolymer may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the content of the perfluoropolymer may be within a range between, and including, any of the minimum and maximum values noted above.

According to still other embodiments, the dielectric coating 205 may include a particular porosity as measured using x-ray diffraction. For example, the porosity of the substrate 205 may be not greater than about 10 vol.%, such as, not greater than about 9 vol.% or not greater than about 8 vol.% or not greater than about 7 vol.% or not greater than about 6 vol.% or even not greater than about 5 vol.%. It will be appreciated that the porosity of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the porosity of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular average thickness. For example, the average thickness of the dielectric coating 205 may be at least about 0.1 microns, such as, at least about 0.5 microns or at least about 1 micron or at least about 2 microns or at least about 3 microns or at least about 4 microns or even at least about 5 microns. According to yet other embodiments, the average thickness of the dielectric coating 205 may be not greater than about 20 microns, such as, not greater than about 18 microns or not greater than about 16 microns or not greater than about 14 microns or not greater than about 12 microns or even not greater than about 10 microns. It will be appreciated that the average thickness of the dielectric coating 205 may be any value between, and including, any of the minimum and maximum values noted above. It will be further appreciated that the average thickness of the dielectric coating 405 may be within a range between, and including, any of the minimum and maximum values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 5 GHz, 20% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 5 GHz, 80% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 10 GHz, 20% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 10 GHz, 80% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 28 GHz, 20% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 28 GHz, 80% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 39 GHz, 20% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 39 GHz, 80% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 76-81 GHz, 20% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about 0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above.

According to yet other embodiments, the dielectric coating 205 may have a particular dissipation factor (Df) as measured in the range between 76-81 GHz, 80% RH. For example, the dielectric coating 205 may have a dissipation factor of not greater than about 0.005, such as, not greater than about 0.004 or not greater than about 0.003 or not greater than about

0.002 or not greater than about 0.0019 or not greater than about 0.0018 or not greater than about 0.0017 or not greater than about 0.0016 or not greater than about 0.0015 or not greater than about 0.0014. It will be appreciated that the dissipation factor of the dielectric coating 205 may be any value between, and including, any of the values noted above. It will be further appreciated that the dissipation factor of the dielectric coating 205 may be within a range between, and including, any of the values noted above. According to yet other embodiments, the dielectric coating 205 may have a particular coefficient of thermal expansion as measured according to IPC-TM-650 2.4.24 Rev. C Glass Transition Temperature and Z-Axis Thermal Expansion by TMA. For example, the dielectric coating 205 may have a coefficient of thermal expansion of not greater than about 80 ppm/°C.

According to yet other embodiments, the copper-clad laminate 201 may have a particular coefficient of thermal expansion as measured according to IPC-TM-650 2.4.24 Rev. C Glass Transition Temperature and Z-Axis Thermal Expansion by TMA. For example, the copper-clad laminate 201 may have a coefficient of thermal expansion of not greater than about 45 ppm/°C.

It will be appreciated that any copper-clad laminate described herein may include additional polymer based layers between the coating and any copper foil layer of the copper-clad laminate. As also noted herein, the additional polymer based layers may include filler (i.e. be filled polymer layers) as described herein or may not include fillers (i.e. be unfilled polymer layers).

Referring next to a method of forming a printed circuit board, FIG. 3 includes a diagram showing a forming method 300 for forming a printed circuit board according to embodiments described herein. According to particular embodiments, the forming method 300 may include a first step 310 of providing a copper foil layer, a second step 320 of combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, a third step 330 of forming the forming mixture into a dielectric coating overlying the copper foil layer to form a copper-clad laminate, and a fourth step 340 of forming the copper-clad laminate into a printed circuit board.

It will be appreciated that all description, details and characteristics provided herein in reference to forming method 100 may further apply to or describe correspond aspects of forming method 300.

Referring now to embodiments of the printed circuit board formed according to forming method 300, FIG. 4 includes diagram of a printed circuit board 400. As shown in FIG. 4, the printed circuit board 400 may include a copper-clad laminate 401, which may include a copper foil layer 402, and a dielectric coating 405 overlying a surface of the copper foil layer 402. According to certain embodiments, the dielectric coating 405 may include a resin matrix component 410 and a ceramic filler component 420.

Again, it will be appreciated that all description provided herein in reference to dielectric coating 205 and/or copper-clad laminate 200 may further apply to correcting aspects of the printed circuit board 200, including all components of printed circuit board 400.

Many different aspects and embodiments are possible. Some of those aspects and embodiments are described herein. After reading this specification, skilled artisans will appreciate that those aspects and embodiments are only illustrative and do not limit the scope of the present invention. Embodiments may be in accordance with any one or more of the embodiments as listed below.

Embodiment 1. A copper-clad laminate comprising: a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises: a resin matrix component; and a ceramic filler component, wherein the ceramic filler component comprises a first filler material, and wherein the dielectric coating has an average thickness of not greater than about 20 microns.

Embodiment 2. A copper-clad laminate comprising: a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises: a resin matrix component; and a ceramic filler component, wherein the ceramic filler component comprises a first filler material, and wherein a particle size distribution of the first filler material comprises: a D_{10} of at least about 0.2 microns and not greater than about 1.6, a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

Embodiment 3. A copper-clad laminate comprising: a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises: a resin matrix component; and a ceramic filler component, wherein the ceramic filler component comprises a first filler material, and wherein the first filler material further comprises a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

Embodiment 4. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein a particle size distribution of the first filler material comprises a D_{10} of at least about 0.2 microns and not greater than about 1.6.

Embodiment 5. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein a particle size distribution of the first filler material comprises a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns.

Embodiment 6. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein a particle size distribution of the first filler material comprises a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

Embodiment 7. The copper-clad laminate of embodiment 1, wherein the first filler material further comprises a mean particle size of not greater than about 10 microns.

Embodiment 8. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the first filler material comprises a mean particle size of not greater than about 10 microns.

Embodiment 9. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the first filler material comprises a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

Embodiment 10. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the first filler material further comprises an average surface area of not greater than about 10 m^2/g.

Embodiment 11. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the first filler material comprises a silica based compound.

Embodiment 12. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the first filler material comprises silica.

Embodiment 13. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the resin matrix comprises a perfluoropolymer.

Embodiment 14. The copper-clad laminate of embodiment 13, wherein the perfluoropolymer comprises a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof.

Embodiment 15. The copper-clad laminate of embodiment 13, wherein the perfluoropolymer comprises polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 16. The copper-clad laminate of embodiment 13, wherein the perfluoropolymer consists of polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 17. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the content of the resin matrix component is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 18. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the content of the resin matrix component is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 19. The copper-clad laminate of embodiment 13, wherein the content of the perfluoropolymer is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 20. The copper-clad laminate of embodiment 13, wherein the content of the perfluoropolymer is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 21. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the content of the ceramic filler component is at least about 30 vol.% for a total volume of the dielectric coating.

Embodiment 22. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the content of the ceramic filler component is not greater than about 57 vol.% for a total volume of the dielectric coating.

Embodiment 23. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the content of the first filler material is at least about 80 vol.% for a total volume of the ceramic filler component.

Embodiment 24. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the content of the first filler material is not greater than about 100 vol.% for a total volume of the ceramic filler component.

Embodiment 25. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the ceramic filler component further comprises a second filler material.

Embodiment 26. The copper-clad laminate of embodiment 25, wherein the second filler material comprises a high dielectric constant ceramic material.

Embodiment 27. The copper-clad laminate of embodiment 26, wherein the high dielectric constant ceramic material has a dielectric constant of at least about 14.

Embodiment 28. The copper-clad laminate of embodiment 26, wherein the ceramic filler component further comprises TiO_2, $SrTiO_3$, $ZrTi_2O_6$, $MgTiO_3$, $CaTiO_3$, $BaTiO_4$ or any combination thereof.

Embodiment 29. The copper-clad laminate of embodiment 25, wherein the content of the second filler material is at least about 1 vol.% for a total volume of the ceramic filler component.

Embodiment 30. The copper-clad laminate of embodiment 25, wherein the content of the second filler material is not greater than about 20 vol.% for a total volume of the ceramic filler component.

Embodiment 31. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the ceramic filler component is at least about 97% amorphous.

Embodiment 32. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the dielectric coating comprises a porosity of not greater than about 10 vol.%.

Embodiment 33. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the copper-clad laminate comprises a porosity of not greater than about 10 vol.%.

Embodiment 34. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the dielectric coating comprises an average thickness of at least about 1 micron.

Embodiment 35. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the dielectric coating comprises an average thickness of not greater than about 20 microns.

Embodiment 36. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 3.5.

Embodiment 37. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 0.001.

Embodiment 38. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the dielectric coating comprises a coefficient of thermal expansion (all axes) of not greater than about 80 ppm/°C.

Embodiment 39. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the copper-clad laminate comprises a peel strength between the copper foil layer and the dielectric coating of at least about 6 lb/in.

Embodiment 40. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the dielectric coating comprises a moisture absorption of not greater than about 0.05%.

Embodiment 41. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the copper foil layer comprises an average thickness of at least about 6 microns.

Embodiment 42. The copper-clad laminate of any one of embodiments 1, 2, and 3, wherein the copper foil layer comprises an average thickness of not greater than about 36 microns.

Embodiment 43. A printed circuit board comprising a copper-clad laminate, wherein the copper-clad laminate comprises: a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises: a resin matrix component; and a ceramic filler component, wherein the ceramic filler component comprises a first filler material, and wherein the dielectric coating has an average thickness of not greater than 20 microns.

Embodiment 44. A printed circuit board comprising a copper-clad laminate, wherein the copper-clad laminate comprises: a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises: a resin matrix component; and a ceramic filler component, wherein the ceramic filler component comprises a first filler material, and wherein a particle size distribution of the first filler material comprises: a D_{10} of at least about 0.2 microns and not greater than about 1.6, a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

Embodiment 45. A printed circuit board comprising a copper-clad laminate, wherein the copper-clad laminate comprises: a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises: a resin matrix component; and a ceramic filler component, wherein the ceramic filler component comprises a first filler material, and wherein the first filler material further comprises a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

Embodiment 46. The printed circuit board of any one of embodiments 43, 44 and 45, wherein a particle size distribution of the first filler material comprises a D_{10} of at least about 0.2 microns and not greater than about 1.6.

Embodiment 47. The printed circuit board of any one of embodiments 43, 44 and 45, wherein a particle size distribution of the first filler material comprises a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns.

Embodiment 48. The printed circuit board of any one of embodiments 43, 44 and 45, wherein a particle size distribution of the first filler material comprises a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

Embodiment 49. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the first filler material further comprises a mean particle size of not greater than about 10 microns.

Embodiment 50. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the first filler material comprises a mean particle size of not greater than about 10 microns.

Embodiment 51. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the first filler material comprises a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

Embodiment 52. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the first filler material further comprises an average surface area of not greater than about 10 m^2/g.

Embodiment 53. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the first filler material comprises a silica based compound.

Embodiment 54. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the first filler material comprises silica.

Embodiment 55. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the resin matrix comprises a perfluoropolymer.

Embodiment 56. The printed circuit board of embodiment 55, wherein the perfluoropolymer comprises a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof.

Embodiment 57. The printed circuit board of embodiment 55, wherein the perfluoropolymer comprises polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 58. The printed circuit board of embodiment 55, wherein the perfluoropolymer consists of polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 59. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the content of the resin matrix component is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 60. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the content of the resin matrix component is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 61. The printed circuit board of embodiment 55, wherein the content of the perfluoropolymer is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 62. The printed circuit board of embodiment 55, wherein the content of the perfluoropolymer is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 63. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the content of the ceramic filler component is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 64. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the content of the ceramic filler component is not greater than about 57 vol.% for a total volume of the dielectric coating.

Embodiment 65. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the content of the first filler material is at least about 80 vol.% for a total volume of the ceramic filler component.

Embodiment 66. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the content of the first filler material is not greater than about 100 vol.% for a total volume of the ceramic filler component.

Embodiment 67. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the ceramic filler component further comprises a second filler material.

Embodiment 68. The printed circuit board of embodiment 67, wherein the second filler material comprises a high dielectric constant ceramic material.

Embodiment 69. The printed circuit board of embodiment 68, wherein the high dielectric constant ceramic material has a dielectric constant of at least about 14.

Embodiment 70. The printed circuit board of embodiment 68, wherein the ceramic filler component further comprises TiO_2, $SrTiO_3$, $ZrTi_2O_6$, $MgTiO_3$, $CaTiO_3$, $BaTiO_4$ or any combination thereof.

Embodiment 71. The printed circuit board of embodiment 67, wherein the content of the second filler material is at least about 1 vol.% for a total volume of the ceramic filler component.

Embodiment 72. The printed circuit board of embodiment 67, wherein the content of the second filler material is not greater than about 20 vol.% for a total volume of the ceramic filler component.

Embodiment 73. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the ceramic filler component is at least about 97% amorphous.

Embodiment 74. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the dielectric coating comprises a porosity of not greater than about 10 vol.%.

Embodiment 75. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the copper-clad laminate comprises a porosity of not greater than about 10 vol.%.

Embodiment 76. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the dielectric coating comprises an average thickness of at least about 1 micron.

Embodiment 77. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the dielectric coating comprises an average thickness of not greater than about 20 microns.

Embodiment 78. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 0.005.

Embodiment 79. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 0.0014.

Embodiment 80. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the dielectric coating comprises a coefficient of thermal expansion (all axes) of not greater than about 80 ppm/°C.

Embodiment 81. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the copper-clad laminate comprises a peel strength between the copper foil layer and the dielectric coating of at least about 6 lb/in.

Embodiment 82. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the dielectric coating comprises a moisture absorption of not greater than about 0.05%.

Embodiment 83. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the copper foil layer comprises an average thickness of at least about 6 microns.

Embodiment 84. The printed circuit board of any one of embodiments 43, 44 and 45, wherein the copper foil layer comprises an average thickness of not greater than about 36 microns.

Embodiment 85. A method of forming a copper-clad laminate, wherein the method comprises: providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, forming the forming mixture into a dielectric coating overlying the copper foil, wherein the dielectric coating has an average thickness of not greater than about 20 microns.

Embodiment 86. A method of forming a copper-clad laminate, wherein the method comprises: providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, forming the forming mixture into a dielectric coating overlying the copper foil, wherein the ceramic filler precursor component comprises a first filler precursor material, and wherein a particle size distribution of the first filler precursor material comprises: a D_{10} of at least about 0.2 microns and not greater than about 1.6 microns, a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

Embodiment 87. A method of forming a copper-clad laminate, wherein the method comprises: providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, forming the forming mixture into a dielectric coating overlying the copper foil, wherein the ceramic filler precursor component comprises a first filler precursor material, and wherein the first filler precursor material further comprises a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler precursor material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler precursor material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler precursor material.

Embodiment 88. The method of any one of embodiments 85, 86, and 87, wherein a particle size distribution of the first filler precursor material comprises a D_{10} of at least about 0.2 microns and not greater than about 1.6 microns.

Embodiment 89. The method of any one of embodiments 85, 86, and 87, wherein a particle size distribution of the first filler precursor material comprises a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns.

Embodiment 90. The method of any one of embodiments 85, 86, and 87, wherein a particle size distribution of the first filler precursor material comprises a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

Embodiment 91. The method of embodiment 85, wherein the first filler precursor material further comprises a mean particle size of not greater than about 10 microns.

Embodiment 92. The method of any one of embodiments 85, 86, and 87, wherein the first filler precursor material comprises a mean particle size of not greater than about 10 microns.

Embodiment 93. The method of any one of embodiments 85, 86, and 87, wherein the first filler precursor material comprises a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler precursor material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler precursor material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler precursor material.

Embodiment 94. The method of any one of embodiments 85, 86, and 87, wherein the first filler precursor material further comprises an average surface area of not greater than about 10 m^2/g.

Embodiment 95. The method of any one of embodiments 85, 86, and 87, wherein the first filler precursor material comprises a silica based compound.

Embodiment 96. The method of any one of embodiments 85, 86, and 87, the first filler precursor material comprises silica.

Embodiment 97. The method of any one of embodiments 85, 86, and 87, wherein the resin matrix precursor component comprises a perfluoropolymer.

Embodiment 98. The method of embodiment 97, wherein the perfluoropolymer comprises a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof.

Embodiment 99. The method of embodiment 97, wherein the perfluoropolymer comprises polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 100. The method of embodiment 97, wherein the perfluoropolymer consists of polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 101. The method of any one of embodiments 85, 86, and 87, wherein the content of the resin matrix precursor component is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 102. The method of any one of embodiments 85, 86, and 87, wherein the content of the resin matrix precursor component is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 103. The method of embodiment 97, wherein the content of the perfluoropolymer is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 104. The method of embodiment 97, wherein the content of the perfluoropolymer is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 105. The method of any one of embodiments 85, 86, and 87, wherein the content of the ceramic filler precursor component is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 106. The method of any one of embodiments 85, 86, and 87, wherein the content of the ceramic filler precursor component is not greater than about 57 vol.% for a total volume of the dielectric coating.

Embodiment 107. The method of any one of embodiments 85, 86, and 87, wherein the content of the first filler precursor material is at least about 80 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 108. The method of any one of embodiments 85, 86, and 87, wherein the content of the first filler precursor material is not greater than about 100 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 109. The method of any one of embodiments 85, 86, and 87, wherein the ceramic filler precursor component further comprises a second filler precursor material.

Embodiment 110. The method of embodiment 109, wherein the second filler precursor material comprises a high dielectric constant ceramic material.

Embodiment 111. The method of embodiment 110, wherein the high dielectric constant ceramic material has a dielectric constant of at least about 14.

Embodiment 112. The method of embodiment 110, wherein the ceramic filler precursor component further comprises TiO_2, $SrTiO_3$, $ZrTi_2O_6$, $MgTiO_3$, $CaTiO_3$, $BaTiO_4$ or any combination thereof.

Embodiment 113. The method of embodiment 109, wherein the content of the second filler precursor material is at least about 1 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 114. The method of embodiment 109, wherein the content of the second filler precursor material is not greater than about 20 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 115. The method of any one of embodiments 85, 86, and 87, wherein the ceramic filler precursor component is at least about 97% amorphous.

Embodiment 116. The method of any one of embodiments 85, 86, and 87, wherein the dielectric coating comprises a porosity of not greater than about 10 vol.%

Embodiment 117. The method of any one of embodiments 85, 86, and 87, wherein the copper-clad laminate comprises a porosity of not greater than about 10 vol.%.

Embodiment 118. The method of any one of embodiments 85, 86, and 87, wherein the dielectric coating comprises an average thickness of at least about 1 micron.

Embodiment 119. The method of any one of embodiments 85, 86, and 87, wherein the dielectric coating comprises an average thickness of not greater than about 20 microns.

Embodiment 120. The method of any one of embodiments 85, 86, and 87, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 0.005.

Embodiment 121. The method of any one of embodiments 85, 86, and 87, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 0.0014.

Embodiment 122. The method of any one of embodiments 85, 86, and 87, wherein the dielectric coating comprises a coefficient of thermal expansion (all axes) of not greater than about 80 ppm/°C.

Embodiment 123. The method of any one of embodiments 85, 86, and 87, wherein the copper-clad laminate comprises a peel strength between the copper foil layer and the dielectric coating of at least about 6 lb/in.

Embodiment 124. The method of any one of embodiments 85, 86, and 87, wherein the dielectric coating comprises a moisture absorption of not greater than about 0.05%.

Embodiment 125. The method of any one of embodiments 85, 86, and 87, wherein the copper foil layer comprises an average thickness of at least about 6 microns.

Embodiment 126. The method of any one of embodiments 85, 86, and 87, wherein the copper foil layer comprises an average thickness of not greater than about 36 microns.

Embodiment 127. A method of forming a printed circuit board, wherein the method comprises: providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, forming the forming mixture into a dielectric coating overlying the copper foil, wherein the dielectric coating has an average thickness of not greater than about 20 microns.

Embodiment 128. A method of forming a printed circuit board, wherein the method comprises: providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, forming the forming mixture into a dielectric coating overlying the copper foil, wherein the ceramic filler precursor component comprises a first filler precursor material, and wherein a particle size distribution of the first filler precursor material comprises: a D_{10} of at least about 0.2 microns and not greater than about 1.6 microns, a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns, and a D_{90} of at least about 0.5 microns and not greater than about 4.7 microns.

Embodiment 129. A method of forming a printed circuit board, wherein the method comprises: providing a copper foil layer, combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture, forming the forming mixture into a dielectric coating overlying the copper foil, wherein the ceramic filler precursor component comprises a first filler precursor material, and wherein the first filler precursor material further comprises a mean particle size of not greater than about 5 microns, and a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler precursor material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler precursor material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler precursor material.

Embodiment 130. The method of any one of embodiments 127, 128, and 129, wherein a particle size distribution of the first filler precursor material comprises a D_{10} of at least about 0.2 microns and not greater than about 1.6 microns.

Embodiment 131. The method of any one of embodiments 127, 128, and 129, wherein a particle size distribution of the first filler precursor material comprises a D_{50} of at least about 0.5 microns and not greater than about 2.7 microns.

Embodiment 132. The method of any one of embodiments 127, 128, and 129, wherein a particle size distribution of the first filler precursor material comprises a D_{90} of at least about 0.8 microns and not greater than about 4.7 microns.

Embodiment 133. The method of embodiment 132, wherein the first filler precursor material further comprises a mean particle size of not greater than about 10 microns.

Embodiment 134. The method of any one of embodiments 127, 128, and 129, wherein the first filler precursor material comprises a mean particle size of not greater than about 10 microns.

Embodiment 135. The method of any one of embodiments 127, 128, and 129, wherein the first filler precursor material comprises a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler precursor material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler precursor material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler precursor material.

Embodiment 136. The method of any one of embodiments 127, 128, and 129, wherein the first filler precursor material further comprises an average surface area of not greater than about 10 m^2/g.

Embodiment 137. The method of any one of embodiments 127, 128, and 129, wherein the first filler precursor material comprises a silica based compound.

Embodiment 138. The method of any one of embodiments 127, 128, and 129, the first filler precursor material comprises silica.

Embodiment 139. The method of any one of embodiments 127, 128, and 129, wherein the resin matrix precursor component comprises a perfluoropolymer.

Embodiment 140. The method of embodiment 139, wherein the perfluoropolymer comprises a copolymer of tetrafluoroethylene (TFE); a copolymer of hexafluoropropylene (HFP); a terpolymer of tetrafluoroethylene (TFE); or any combination thereof.

Embodiment 141. The method of embodiment 139, wherein the perfluoropolymer comprises polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 142. The method of embodiment 139, wherein the perfluoropolymer consists of polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer resin (PFA), fluorinated ethylene propylene (FEP), or any combination thereof.

Embodiment 143. The method of any one of embodiments 127, 128, and 129, wherein the content of the resin matrix precursor component is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 144. The method of any one of embodiments 127, 128, and 129, wherein the content of the resin matrix precursor component is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 145. The method of embodiment 139, wherein the content of the perfluoropolymer is at least about 50 vol.% for a total volume of the dielectric coating.

Embodiment 146. The method of embodiment 139, wherein the content of the perfluoropolymer is not greater than about 63 vol.% for a total volume of the dielectric coating.

Embodiment 147. The method of any one of embodiments 127, 128, and 129, wherein the content of the ceramic filler precursor component is at least about 30 vol.% for a total volume of the dielectric coating.

Embodiment 148. The method of any one of embodiments 127, 128, and 129, wherein the content of the ceramic filler precursor component is not greater than about 57 vol.% for a total volume of the dielectric coating.

Embodiment 149. The method of any one of embodiments 127, 128, and 129, wherein the content of the first filler precursor material is at least about 80 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 150. The method of any one of embodiments 127, 128, and 129, wherein the content of the first filler precursor material is not greater than about 100 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 151. The method of any one of embodiments 127, 128, and 129, wherein the ceramic filler precursor component further comprises a second filler precursor material.

Embodiment 152. The method of embodiment 151, wherein the second filler precursor material comprises a high dielectric constant ceramic material.

Embodiment 153. The method of embodiment 152, wherein the high dielectric constant ceramic material has a dielectric constant of at least about 14.

Embodiment 154. The method of embodiment 152, wherein the ceramic filler precursor component further comprises TiO_2, $SrTiO_3$, $ZrTi_2O_6$, $MgTiO_3$, $CaTiO_3$, $BaTiO_4$ or any combination thereof.

Embodiment 155. The method of embodiment 151, wherein the content of the second filler precursor material is at least about 1 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 156. The method of embodiment 151, wherein the content of the second filler precursor material is not greater than about 20 vol.% for a total volume of the ceramic filler precursor component.

Embodiment 157. The method of any one of embodiments 127, 128, and 129, wherein the ceramic filler precursor component is at least about 97% amorphous.

Embodiment 158. The method of any one of embodiments 127, 128, and 129, wherein the dielectric coating comprises a porosity of not greater than about 10 vol.%.

Embodiment 159. The method of any one of embodiments 127, 128, and 129, wherein the copper-clad laminate comprises a porosity of not greater than about 10 vol.%.

Embodiment 160. The method of any one of embodiments 127, 128, and 129, wherein the dielectric coating comprises an average thickness of at least about 1 micron.

Embodiment 161. The method of any one of embodiments 127, 128, and 129, wherein the dielectric coating comprises an average thickness of not greater than about 20 microns.

Embodiment 162. The method of any one of embodiments 127, 128, and 129, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 0.005.

Embodiment 163. The method of any one of embodiments 127, 128, and 129, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 0.0014.

Embodiment 164. The method of any one of embodiments 127, 128, and 129, wherein the dielectric coating comprises a coefficient of thermal expansion (all axes) of not greater than about 80 ppm/°C.

Embodiment 165. The method of any one of embodiments 127, 128, and 129, wherein the copper-clad laminate comprises a peel strength between the copper foil layer and the dielectric coating of at least about 6 lb/in.

Embodiment 166. The method of any one of embodiments 127, 128, and 129, wherein the dielectric coating comprises a moisture absorption of not greater than about 0.05%.

Embodiment 167. The method of any one of embodiments 127, 128, and 129, wherein the copper foil layer comprises an average thickness of at least about 6 microns.

Embodiment 168. The method of any one of embodiments 127, 128, and 129, wherein the copper foil layer comprises an average thickness of not greater than about 36 microns.

Note that not all of the activities described above in the general description or the examples are required, that a portion of a specific activity may not be required, and that one or more further activities may be performed in addition to those described. Still further, the order in which activities are listed is not necessarily the order in which they are performed.

Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any feature(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature of any or all the claims.

The specification and illustrations of the embodiments described herein are intended to provide a general understanding of the structure of the various embodiments. The specification and illustrations are not intended to serve as an exhaustive and comprehensive description of all of the elements and features of apparatus and systems that use the structures or methods described herein. Separate embodiments may also be provided in combination in a single embodiment, and conversely, various features that are, for brevity, described in the context of a single embodiment, may also be provided separately or in any subcombination. Further, reference to values stated in ranges includes each and every value within that range. Many other embodiments may be apparent to skilled artisans only after reading this specification. Other embodiments may be used and derived from the disclosure, such that a structural substitution, logical substitution, or another change may be made without departing from the scope of the disclosure. Accordingly, the disclosure is to be regarded as illustrative rather than restrictive.

WHAT IS CLAIMED IS:

1. A copper-clad laminate comprising:

a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises:

a resin matrix component; and

a ceramic filler component,

wherein the ceramic filler component comprises a first filler material, and wherein the dielectric coating has an average thickness of not greater than about 20 microns.

2. The copper-clad laminate of claim 1, wherein the first filler material further comprises a mean particle size of at not greater than about 10 microns.

3. The copper-clad laminate of claim 1, wherein the first filler material comprises a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

4. The copper-clad laminate of claim 1, wherein the first filler material further comprises an average surface area of not greater than about 10 m^2/g.

5. The copper-clad laminate of claim 1, wherein the first filler material comprises a silica based compound.

6. The copper-clad laminate of claim 1, wherein the first filler material comprises silica.

7. The copper-clad laminate of claim 1, wherein the resin matrix comprises a perfluoropolymer.

8. The copper-clad laminate of claim 1, wherein the content of the resin matrix component is at least about 50 vol.% and not greater than about 63 vol.% for a total volume of the dielectric coating.

9. The copper-clad laminate of claim 1, wherein the content of the ceramic filler component is at least about 30 vol.% and not greater than about 57 vol.% for a total volume of the dielectric coating.

10. The copper-clad laminate of claim 1, wherein the content of the first filler material is at least about 80 vol.% and not greater than about 100 vol.% for a total volume of the ceramic filler component.

11. The copper-clad laminate of claim 1, wherein the dielectric coating comprises a dissipation factor (5 GHz, 20% RH) of not greater than about 3.5.

12. A printed circuit board comprising a copper-clad laminate, wherein the copper-clad laminate comprises:

a copper foil layer, and a dielectric coating overlying the copper foil layer, wherein the dielectric coating comprises:

a resin matrix component; and

a ceramic filler component,

wherein the ceramic filler component comprises a first filler material, and

wherein the dielectric coating has an average thickness of not greater than 20 microns.

13. The printed circuit board of claim 12, wherein the first filler material further comprises a mean particle size of at not greater than about 10 microns.

14. The printed circuit board of claim 12, wherein the first filler material comprises a particle size distribution span (PSDS) of not greater than about 5, where PSDS is equal to $(D_{90}-D_{10})/D_{50}$, where D_{90} is equal to a D_{90} particle size distribution measurement of the first filler material, D_{10} is equal to a D_{10} particle size distribution measurement of the first filler material, and D_{50} is equal to a D_{50} particle size distribution measurement of the first filler material.

15. A method of forming a copper-clad laminate, wherein the method comprises:

providing a copper foil layer,

combining a resin matrix precursor component and a ceramic filler precursor component to form a forming mixture,

forming the forming mixture into a dielectric coating overlying the copper foil,

wherein the dielectric coating has an average thickness of not greater than about 20 microns.

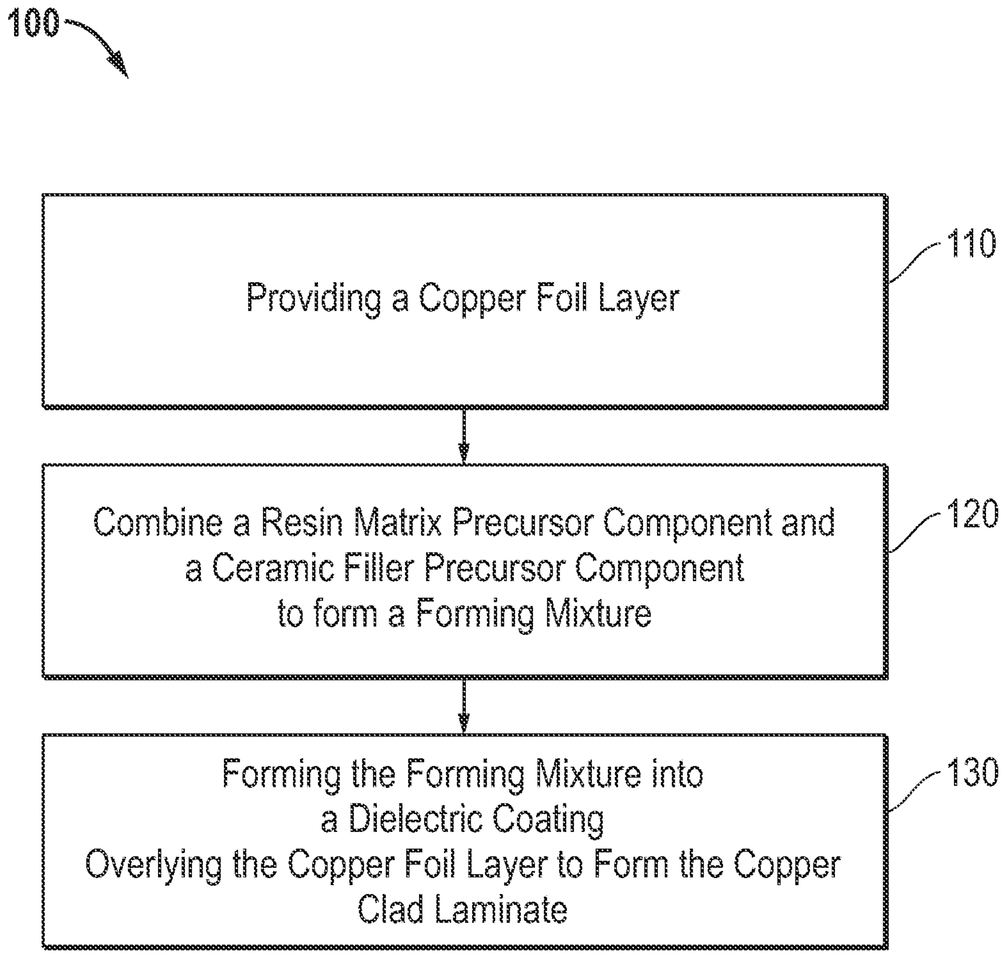
100
Providing a Copper Foil Layer
110
Combine a Resin Matrix Precursor Component and a Ceramic Filler Precursor Component to form a Forming Mixture
120
Forming the Forming Mixture into a Dielectric Coating Overlying the Copper Foil Layer to Form the Copper Clad Laminate
130

FIG. 1

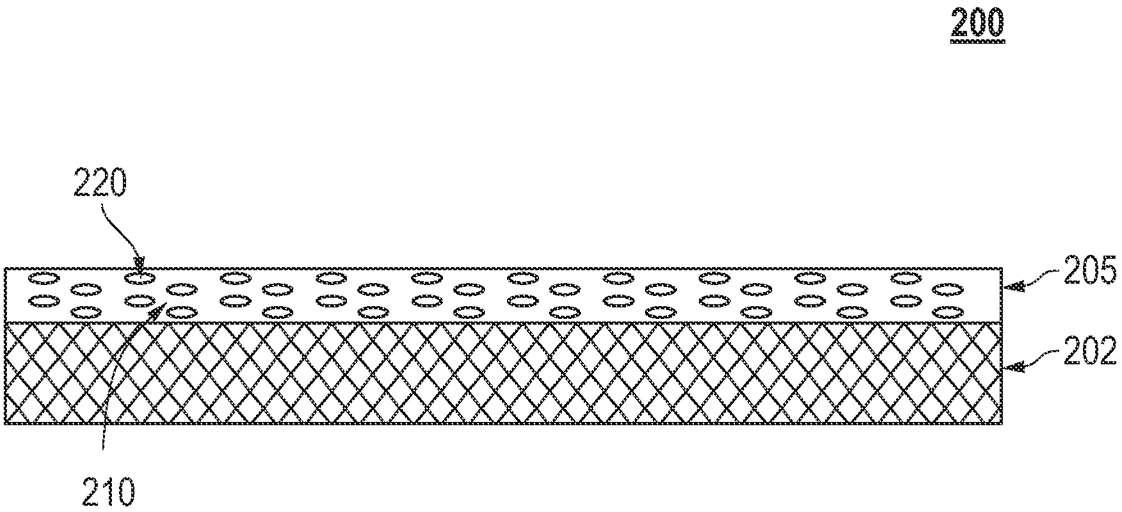

FIG. 2

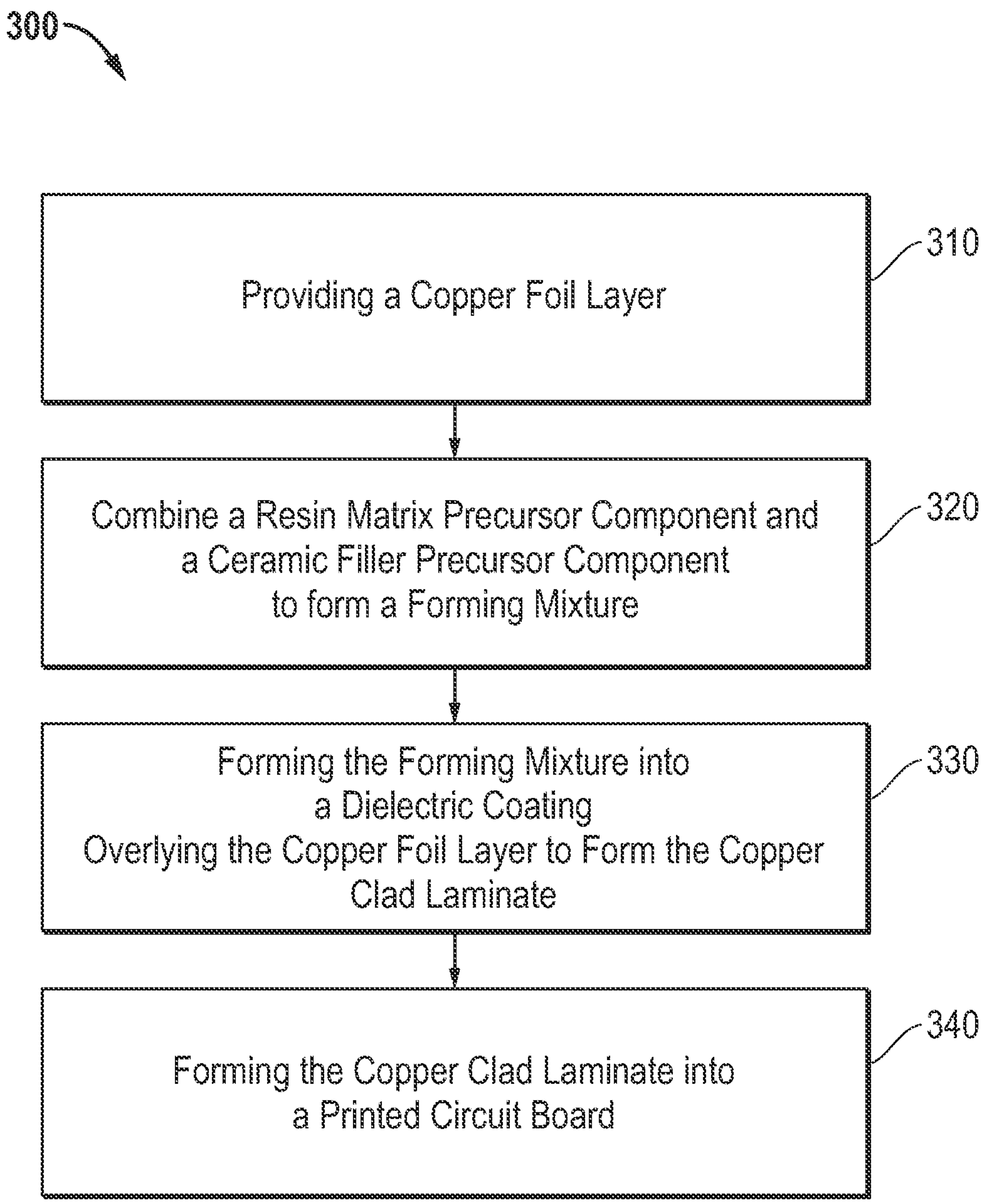
300
Providing a Copper Foil Layer
310
Combine a Resin Matrix Precursor Component and a Ceramic Filler Precursor Component to form a Forming Mixture
320
Forming the Forming Mixture into a Dielectric Coating Overlying the Copper Foil Layer to Form the Copper Clad Laminate
330
Forming the Copper Clad Laminate into a Printed Circuit Board
340

FIG. 3

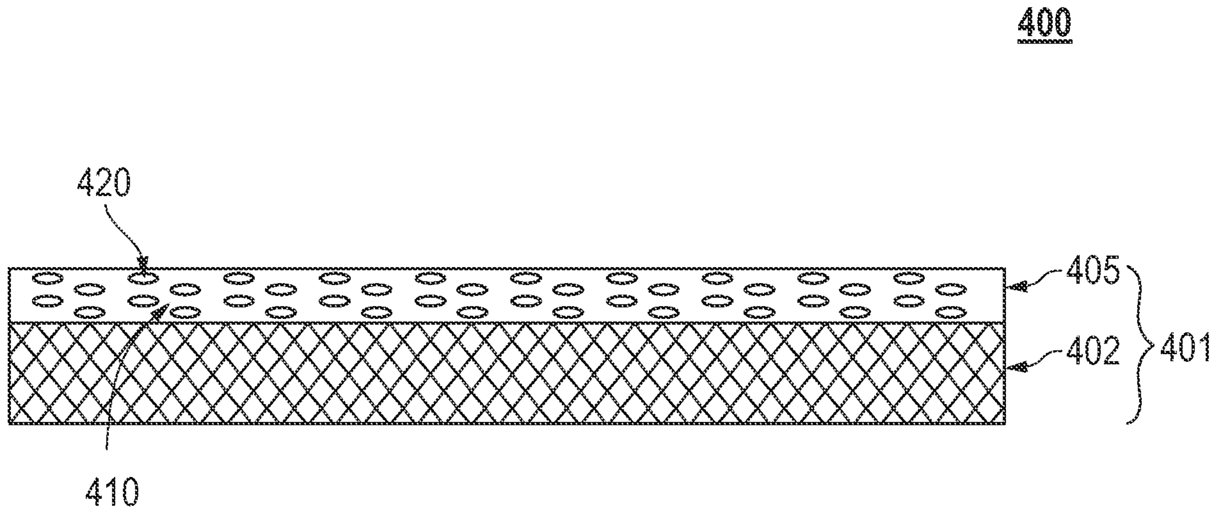

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/070954

A. CLASSIFICATION OF SUBJECT MATTER

H05K 1/09(2006.01)i; **H05K 1/03**(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H05K 1/09(2006.01); B05D 5/00(2006.01); B32B 15/08(2006.01); C01B 33/12(2006.01); C09C 1/30(2006.01); H01B 3/40(2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: dielectric substrate, copper-clad laminate, resin matrix, ceramic filler, copper layer, thickness, particle, size, distribution, average surface area, volume

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2005-0244662 A1 (ALLEN F. HORN III et al.) 03 November 2005 (2005-11-03) Paragraphs 2-5; claims 1, 6; and figure 1.	1-15
Y	US 2012-0123021 A1 (TOSHIHIRO YANO et al.) 17 May 2012 (2012-05-17) Paragraphs 28, 55, 151, 190; and claim 1.	1-15
A	KR 10-2015-0006713 A (SAMSUNG ELECTRO-MECHANICS CO., LTD.) 19 January 2015 (2015-01-19) Claims 1-15; and figures 1-4.	1-15
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A	KR 10-2006-0127172 A (DEGUSSA GMBH) 11 December 2006 (2006-12-11) Claims 1-7.	1-15

☐ Further documents are listed in the continuation of Box C.   ☑ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "D" document cited by the applicant in the international application
- "E" earlier application or patent but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 November 2021	**16 November 2021**

Name and mailing address of the ISA/KR	Authorized officer
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2021/070954

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