CLAIMS

What is claimed is:

1. An ink adapted for forming conductive elements, the ink comprising:

a plurality of nanoparticles that comprise copper, the nanoparticles having a diameter of less than 20 nanometers, each nanoparticle comprising at least a partial coating of a surfactant configured to separate adjacent nanoparticles, wherein the plurality of nanoparticles are configured to fuse to one another when one nanoparticle is pressed against another nanoparticle with an interparticle pressure, the interparticle pressure is an interparticle force divided by a nominal cross-sectional area of a nanoparticle, and the interparticle pressure is less than 14000 kilopascals (kPa); and

a carrier.

2. The ink of claim 1, wherein the nanoparticles have a diameter of less than 10 nanometers.

3. The ink of claim 2, wherein the nanoparticles have a diameter in the range of 1-7 nanometers.

4. The ink of claim 3, wherein the nanoparticles have a diameter in the range of 3-5 nanometers.

5. The ink of claim 1, wherein the nanoparticles are configured to fuse to one another when one nanoparticle strikes another nanoparticle with a relative velocity greater than 0.5 meter per second.

6. The ink of claim 5, wherein the nanoparticles are configured to fuse to one another when one nanoparticle strikes another nanoparticle with a relative velocity greater than 1.0 meter per second.

7. The ink of claim 1, wherein the nanoparticles are configured to fuse to one another when ~~one nanoparticle is pressed against another nanoparticle with an interparticle pressure, considered as an interparticle force divided by a nominal cross-sectional area of a nanoparticle, that~~the interparticle pressure is less than 600 kilopascals (kPa).

8. The ink of claim 1~~7~~, wherein the nanoparticles are configured to fuse to one another when the interparticle pressure is less than 5000 kilopascals (kPa).

~~9. The ink of claim 8, wherein the nanoparticles are configured to fuse to one another when the interparticle pressure is less than 14000 kilopascals (kPa).~~

~~10.~~9. A circuit assembly comprising:

a substrate having a maximum exposure temperature of less than 200 °C; and

a first layer of formed metal coupled to the substrate, the first layer of formed metal comprising at least partially fused nanoparticles that comprise copper and had a diameter of less than 50 nanometers prior to being fused~~.~~;

a first layer of a nonconductive material over at least a portion of the first layer of formed metal;

a second layer of formed metal over the first nonconductive layer, the second layer comprising the at least partially fused nanoparticles; and

at least one via that penetrates the first nonconductive layer and electrically connects the first and second metal layers, the via comprising fused nanoparticles that comprise copper.

~~11.~~10. The circuit assembly of claim 9~~10~~, wherein the nanoparticles had a diameter of less than 20 nanometers prior to being fused.

~~12.~~11. The circuit assembly of claim 10~~11~~, wherein the nanoparticles had a diameter of less than 10 nanometers prior to being fused.

~~13.~~12. The circuit assembly of claim 11~~12~~, wherein the nanoparticles had a diameter had a diameter in the range of 1-7 nanometers prior to being fused.

~~14.~~13. The circuit assembly of claim 12~~13~~, wherein the nanoparticles had a diameter had a diameter in the range of 3-5 nanometers prior to being fused.

~~15.~~14. The circuit assembly of claim 9~~10~~, wherein the substrate is flexible.

~~16.~~15. The circuit assembly of claim 9~~10~~, wherein the substrate has a maximum exposure temperature of less than 70 °C.

~~17. The circuit assembly of claim 10, further comprising:~~

~~a first layer of a nonconductive material over at least a portion of the first layer of formed metal; and~~

~~a second layer of formed metal over the first nonconductive layer, the second layer comprising the at least partially fused nanoparticles.~~

~~18. The circuit assembly of claim 17, further comprising at least one via that penetrates the first nonconductive layer and electrically connects the first and second metal layers, the via comprising fused nanoparticles that comprise copper.~~

~~19.~~16. The circuit assembly of claim ~~9~~10, wherein the first layer of formed metal forms at least a portion of a passive device selected from the set of a resistor, a capacitor, an inductor, and a diode.

~~20.~~17. The circuit assembly of claim ~~9~~10, wherein the first layer of formed metal forms at least a portion of a transistor.

~~21.~~18. The circuit assembly of claim ~~9~~10, wherein the first layer of formed metal forms at least a portion of a battery.

~~22.~~19. The circuit assembly of claim ~~9~~10, further comprising discrete electrical components.

~~23.~~20. A circuit-printing device comprising:

a sprayer configured to emit a plurality of drops of a mixture comprising nanoparticles that comprise copper and have a diameter of less than 20 nanometers toward a substrate with sufficient velocity that the nanoparticles at least partially fuse with each other upon impact with the substrate and form a plurality of dots on the substrate, wherein each dot comprises a layer of at least partially fused nanoparticles and overlapping dots are fused to each other.

~~24.~~21. The circuit-printing device of claim ~~20~~23, wherein the nanoparticles have a diameter of less than 10 nanometers.

~~25.~~22. The circuit-printing device of claim ~~21~~24, wherein the nanoparticles have a diameter in the range of 1-7 nanometers.

~~26.~~23. The circuit-printing device of claim ~~22~~25, wherein the nanoparticles have a diameter in the range of 3-5 nanometers.

~~27.~~24. The circuit-printing device of claim ~~20~~23, wherein the velocity of the emitted drops is greater than 0.5 meter per second.

~~28.~~25. The circuit-printing device of claim ~~24~~27, wherein the velocity of the emitted drops is greater than 1.0 meter per second.

~~29.~~26. The circuit-printing device of claim ~~20~~23, further configured to create a conductive pattern of metal without exposure of the substrate to a temperature greater than 200 °C.

~~30.~~27. The circuit-printing device of claim 26~~29~~, further configured to create a conductive pattern of metal without exposure of the substrate to a temperature greater than 70 °C.

~~31.~~28. A method of creating a conductive element on a substrate, the method comprising the step of:

spraying a plurality of drops of a mixture comprising nanoparticles that comprise copper and have a diameter of less than 20 nanometers toward a substrate with sufficient velocity that the nanoparticles at least partially fuse with each other upon impact with the substrate and form a plurality of dots on the substrate, wherein each dot comprises a layer of fused nanoparticles and overlapping dots are fused to each other.

~~32.~~29. The method of claim 28~~31~~, wherein the nanoparticles have a diameter of less than 10 nanometers.

~~33.~~30. The method of claim 29~~32~~, wherein the nanoparticles have a diameter in the range of 1-7 nanometers.

~~34.~~31. The method of claim 30~~33~~, wherein the nanoparticles have a diameter in the range of 3-5 nanometers.

~~35.~~32. The method of claim 28~~31~~, wherein the temperature of the substrate remains within 20 °C of ambient temperature while the nanoparticles are fusing to each other.

~~36.~~33. The method of claim 28~~31~~, wherein the temperature of the substrate remains below 200 °C while the nanoparticles are fusing to each other.

~~37.~~34. The method of claim 33~~36~~, wherein the temperature of the substrate remains below 70 °C while the nanoparticles are fusing to each other.

~~38.~~35. The method of claim 28~~31~~, wherein the substrate is flexible.

~~39.~~36. The method of claim 28~~31~~, further comprising the step of applying a coating of a protective material over the fused nanoparticles.

~~40.~~37. The method of claim 28~~31~~, wherein the drops are sprayed with a velocity that is greater than 0.5 meter per second.

41.38. The method of claim 3740, wherein the drops are sprayed with a velocity that is greater than 1.0 meter per second.

42.39. A method of creating a conductive element on a substrate, the method comprising the steps of:

applying a layer of a mixture comprising nanoparticles that comprise copper and have a diameter of less than 20 nanometers over at least a portion of a surface of a substrate, wherein the applying induces at least partial fusion of a portion of the nanoparticles; and

at least partially fusing the nanoparticles together in at least a portion of the mixture layer.

43.40. The method of claim 3942, wherein the nanoparticles have a diameter of less than 10 nanometers.

44.41. The method of claim 4043, wherein the nanoparticles have a diameter in the range of 1-7 nanometers.

45.42. The method of claim 4144, wherein the nanoparticles have a diameter in the range of 3-5 nanometers.

46.43. The method of claim 3942, wherein the step of fusing comprises directing a beam of optical radiation onto a portion of the mixture layer.

47.44. The method of claim 4346, wherein the optical radiation has a frequency band that is at least partially within the absorption band of the nanoparticles.

48.45. The method of claim 3942, wherein the step of fusing comprises applying pressure to the mixture layer.

49.46. The method of claim 4548, wherein the pressure is applied by compressing the mixture layer with a form.

50.47. The method of claim 4548, wherein the pressure is applied by dynamically nanoinscribing a pattern over the mixture layer.

51.48. The method of claim 4548, wherein the pressure is applied by burnishing at least a portion of the mixture layer with a roller.

~~52.~~49. The method of claim 48~~51~~, wherein burnishing comprises rotating the roller such that a surface of the roller that is in contact with the mixture has a velocity greater than zero with respect to the substrate.

~~53.~~50. The method of claim 45~~48~~, wherein the pressure is applied by burnishing at least a portion of the mixture layer with a ball.

~~54.~~51. The method of claim 50~~53~~, wherein:

the step of applying comprises applying a layer of the mixture to an inside surface of a cylindrical passage through the substrate; and

the step of fusing comprises passing the ball through the passage.

~~55.~~52. The method of claim 51~~54~~, wherein:

the cylindrical passage has an inside surface with an inside diameter; and

the ball has a diameter that is greater than or equal to the inside diameter of the cylindrical passage.

~~56.~~53. The method of claim 51~~54~~, wherein the step of fusing comprises rotating the ball such that a surface of the ball that is in contact with the mixture has a velocity greater than zero with respect to the inside surface of the cylindrical passage.

~~57.~~54. The method of claim 45~~48~~, wherein:

the step of applying comprises providing a quantity of the mixture onto the substrate and spreading the mixture with a tool drawn across the substrate; and

the application of pressure is accomplished by pressing the tool against the substrate as the tool is drawn across the substrate.

~~58.~~55. The method of claim 39~~42~~, further comprising the step of removing the unfused portion of the mixture layer.

~~59.~~56. The method of claim 39~~42~~, wherein the step of applying comprises applying the mixture in a pattern.

~~60.~~57. The method of claim 56~~59~~, wherein the step of applying a patterned layer of the mixture comprises forcing the mixture out of a nozzle onto the surface of the substrate.

~~61.~~58. The method of claim 5659, wherein the step of fusing comprises illuminating the patterned mixture with a source of optical energy.

~~62.~~59. The method of claim 5659, wherein the step of fusing comprises compressing the patterned mixture against the substrate.

~~63.~~60. The method of claim 5659, wherein the step of fusing comprises heating the patterned mixture to a temperature that is above ambient and below 200 °C.

~~64.~~61. The method of claim 6063, wherein the step of fusing comprises heating the patterned mixture to a temperature that is above ambient and below 70 °C.

~~65.~~62. The method of claim 6164, wherein the step of applying a patterned layer of the mixture comprises applying the mixture to a transfer element and then transferring the mixture from the transfer element to the substrate.

~~66.~~63. The method of claim 6265, wherein the step of fusing the nanoparticles together comprises pressing the transferred patterned mixture against the substrate.

~~67.~~64. The method of claim 3942, wherein the temperature of the substrate remains below 200 °C while the conductive element is formed on the substrate.

~~68.~~65. The method of claim 6467, wherein while the conductive element is formed on the substrate 70 °C while the conductive element is formed on the substrate.

~~69.~~66. The method of claim 6568, wherein the temperature of the substrate remains within 20 °C of ambient temperature while the conductive element is formed on the substrate.

~~70.~~67. The method of claim 3942, wherein the step of applying comprises spin-coating the substrate with the mixture.

~~71.~~68. The method of claim 3942, wherein the step of applying comprises spraying the mixture onto the substrate.

~~72.~~69. The method of claim 3942, wherein the step of applying comprises drawing a squeegee across the substrate.

~~73.~~70. A circuit-printing device comprising:

a first sprayer configured to emit a plurality of drops of a first mixture comprising nanoparticles that comprise copper and have a diameter of less than 50 nanometers, each nanoparticle comprising at least a partial coating of a surfactant configured to separate adjacent nanoparticles, onto a substrate; and

a second sprayer configured to emit a plurality of drops of a second mixture comprising a dispersant configured to displace at least a portion of the surfactant from at least a portion of the nanoparticles previously applied to the substrate upon impact with the applied nanoparticles such that at least a portion of the applied nanoparticles at least partially fuse with each other.

~~74.~~71. The circuit-printing device of claim 7073, wherein the nanoparticles have a diameter of less than 20 nanometers.

~~75.~~72. The circuit-printing device of claim 7174, wherein the nanoparticles have a diameter of less than 10 nanometers.

~~76.~~73. The circuit-printing device of claim 7275, wherein the nanoparticles have a diameter in the range of 1-7 nanometers.

~~77.~~74. The circuit-printing device of claim 7376, wherein the nanoparticles have a diameter in the range of 3-5 nanometers.

~~78.~~75. The circuit-printing device of claim 7073, further configured to create a conductive pattern of metal without exposure of the substrate to a temperature greater than 200 °C.

~~79.~~76. The circuit-printing device of claim 7578, further configured to create a conductive pattern of metal without exposure of the substrate to a temperature greater than 70 °C.