circuit elements on substrates for electronic assemblies. The methods of printing and forming circuit elements from copper nanoparticles as described herein also enable finer pitch circuits, i.e. having small separation distances between conductive elements, than possible with other processes. Circuit elements formed from copper nanoparticles may include passive devices such as resistors, capacitors, and inductors, active devices such as transistors, Radio Frequency (RF) elements such as antennae, reflectors, and waveguides, other circuit elements such as ground and power planes, shielding, and signal paths, and even complete devices such as a Radio Frequency IDentification (RFID) tag.

[0008a] In one aspect, there is provided 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.

[0008b] In one aspect, there is provided 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.

[0008c] In one aspect, there is provided 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.

[0008d] In one aspect, there is provided 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.

[0008e] In one aspect, there is provided 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.

[0008f] In one aspect, there is provided 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.

[0009] In certain embodiments, a circuit element is disclosed that comprises a first layer of formed metal comprising fused nanoparticles that comprise copper and had a diameter of less than 20 nanometers prior to being fused.

[0010] In certain embodiments, a circuit assembly is disclosed that comprises a substrate and a first layer of formed metal coupled to the substrate, the first layer of formed metal comprising fused nanoparticles that comprise copper and had a diameter of less than 20 nanometers prior to being fused.

[0011] In certain embodiments, a circuit-printing device is disclosed that comprises 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 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.

[0012] In certain embodiments, a method of creating a conductive element on a substrate is disclosed. 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 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.

[0013] In certain embodiments, a method of creating a conductive element on a substrate is disclosed. 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