

CLAIMS

1. A method for forming structures upon a substrate, the method comprising:
 - 5 depositing fluid onto a substrate so as to define a wetted region, the fluid containing electrically polarizable nanoparticles;
applying an alternating electric field to the fluid on the region, using a first electrode and a second electrode, so that a plurality of the nanoparticles are assembled to form an elongate structure extending from the first electrode
 - 10 towards the second electrode; and
removing the fluid such that the elongate structure remains upon the substrate, further comprising, during the step of applying the alternating electric field, increasing the separation between the first and second electrodes by moving the second electrode away from the first electrode so as to further extend the
 - 15 elongate structure towards the second electrode.
2. A method according to claim 1, wherein the relationship between the rate at which the length of the assembled elongate structure is increased and the rate at which the separation between the first and second electrodes is increased
- 20 causes the separation between an end part of the structure and an electrode to be such that the electric field in a region of the fluid proximal to the electrode and the end part of the structure causes mobile nanoparticles in that region to assemble upon the end part of the structure.
- 25 3. A method according to claim 1 or claim 2, further comprising monitoring the rate at which the length of the elongate structure is increasing; and adjusting the properties of the alternating electric field in accordance with the monitored rate, such that the length of the elongate structure is increased at a predetermined rate.
- 30 4. A method according to any of the preceding claims, wherein when applying the electric field to the fluid each of the first and second electrodes is in contact with the fluid at a respective first and second position within the fluid.

5. A method according to claim 4, wherein an end part of the first electrode is positioned at the first position such that a first end of the elongate structure is positioned at a predetermined first end position upon the substrate.
- 5 6. A method according to any of the preceding claims, wherein the electrodes are shaped such that each electrode acts as an electric monopole thereby producing an inhomogeneous electric field in the fluid when an electric potential is applied to the electrodes.
- 10 7. A method according to any of the preceding claims, wherein the electrodes comprise a material that is unreactive with the fluid in the presence of the electric field.
8. A method according to any of the preceding claims, wherein at least one
15 of the electrodes has an elongate shape comprising a pointed end, and wherein applying an alternating electric field to the fluid comprises bringing the pointed end of each of the electrodes into contact with the fluid.
9. A method according to claim 8, wherein the pointed end has a diameter
20 of 1–100 μm , and wherein the length of the pointed end is greater than the maximum height of the surface of the fluid above the substrate.
10. A method according to any of the preceding claims, wherein the electric field is applied such that a dielectrophoretic force is exerted upon the plurality of
25 nanoparticles.
11. A method according to any of the preceding claims, wherein the electric field causes mobile nanoparticles within the fluid to be attracted via a dielectrophoretic force to the assembled structure.
- 30 12. A method according to any of the preceding claims, wherein mobile nanoparticles within the fluid are attracted to an end part of the assembled elongate structure that is distal from the first electrode, and wherein the length of

the elongate structure is increased by way of mobile nanoparticles progressively being attached to the end part of the structure.

13. A method according to any of the preceding claims, wherein the electric
5 field has a DC bias, and wherein the DC bias is such that a first end of the structure is formed by mobile nanoparticles within the fluid attaching to the first electrode.

14. A method according to any of the preceding claims, wherein the first
10 electrode or the second electrode comprises a conduit, and wherein the fluid is deposited onto the substrate via the conduit.

15. A method according to claim 14 when dependent upon claim 1, wherein
15 the fluid is deposited onto the substrate via the conduit while the electrode comprising the conduit is moved away from the other electrode.

16. A method according to any of the preceding claims, wherein the
alternating electric field has a frequency in the range 100–1,000,000 Hz, and an
amplitude in the range 1–10,000 Vm⁻¹.

17. A method according to any of the preceding claims, wherein the
alternating electric field is applied to the fluid by applying an alternating electric
potential across the first and second electrodes, the potential having a DC bias
in the range 1 mV–10 V.

18. A method according to any of the preceding claims, wherein the first and
second electrodes are connected to a controller configured to control an
alternating electric current between the electrodes such that the current has an
AC amplitude in the range 1–10,000 µA and a DC bias in the range 0.1–1,000
30 µA.

19. A method according to claim 18, wherein the potentiometer is configured
to control the alternating electric current such that the AC amplitude is in the
range 10–1,000 µA and the DC bias is in the range 1–100 µA.

20. A method according to any of the preceding claims, wherein the width of the wetted region has a minimum width in the range 1–1,000 μm .
- 5 21. A method according to any of the preceding claims, wherein the wetted region has a shape corresponding to a predetermined geometry, and the elongate structure formed within the fluid on the region has a shape corresponding to the predetermined geometry.
- 10 22. A method according to any of the preceding claims, further comprising moving the second electrode along a path corresponding to the shape of the wetted region during the assembly of the elongate structure such that the shape of the assembled elongate structure corresponds to the shape of the path.
- 15 23. A method according to any of the preceding claims, comprising moving the second electrode along a predetermined path corresponding to the shape of the wetted region on the substrate, thereby assembling the structure such that the structure extends along the predetermined path from a first end position to a second end position within the region.
- 20 24. A method according to any of the preceding claims, wherein the step of applying the electric field is repeated for fluid deposited on a second wetted region on the substrate, so as to form a second structure.
- 25 25. A method according to claim 24, wherein the first and second regions overlap such that the structure formed on the second region may be formed such that it is connected to the structure formed on the first region.
- 30 26. A method according to claim 24 or claim 25, wherein the second structure extends from a first end position within the second region to a second end position within the second region, and wherein either of the first or second end positions of the second region coincides with the structure formed on the first region.

27. A method according to any of claims 24 to 26, wherein the fluid is deposited on the second region after the fluid is deposited upon the first region.

28. A method according to any of claims 24 to 27, wherein fluid is removed
5 from the first region prior to the fluid being deposited upon the second region.

29. A method according to any of claims 24 to 28, further comprising forming a respective structure within each of a plurality of adjacent regions on the substrate, such that each structure is connected to at least one other structure.
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30. A method according to any of claim 29, wherein the structures within the plurality of regions are connected together such that they form a compound structure in accordance with a predetermined geometry.

15 31. A method according to any of the preceding claims, wherein an alternating electric field is applied to fluid on a plurality of regions, using a first electrode and a second electrode in each of the respective regions, so that an elongate structure is formed in each region.

20 32. A method according to claim 31, wherein the electric field is applied to the fluid on at least two of the plurality of regions at the same time, so as to form at least two structures simultaneously.

33. A method according to claim 31 or claim 32, wherein the plurality of
25 electrodes used to apply the electric field to the fluid on each of the plurality of regions is arranged such that the plurality of elongate structures formed in the regions are joined together to form a compound structure.

34. A method according to any of the proceeding claims, wherein the
30 substrate surface comprises an electrically insulating material.

35. A method according to any of the proceeding claims, wherein the substrate surface comprises any of glass, polyethylene terephthalate, and polyethylene naphthalate.

36. A method according to any of the proceeding claims, wherein the surface of the substrate within the wetted region has a roughness average in the range 1–10 μm .

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37. A method according to any of the preceding claims, wherein the fluid comprises a solvent, a surfactant and an organic binder.

38. A method according to any of the preceding claims, wherein the mass
10 fraction of the nanoparticles within the fluid is in the range 0.001%–10%.

39. A method according to claim 38, wherein the mass fraction of the nanoparticles within the fluid is in the range 0.02%–5%.

15 40. A method according to any of the preceding claims, wherein, prior to the application of the electric field, the nanoparticles are uniformly distributed throughout the fluid on the region.

41. A method according to any of the preceding claims, wherein depositing
20 the fluid containing the nanoparticles onto the substrate comprises: depositing fluid onto the substrate, and subsequently adding nanoparticles to the fluid.

42. A method according to any of the preceding claims, wherein the fluid is removed by way of evaporation.

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43. A method according to claim 42, wherein the rate of fluid evaporation is increased by way of applying heat to the fluid.

44. A method according to claim 43, wherein applying heat to the fluid causes
30 the adhesion of the assembled structure to the substrate to increase.

45. A method according to any of the preceding claims, wherein the method further comprises a sintering process.

46. A method according to claim 45, wherein the sintering process causes assembled nanoparticles to coalesce so as to increase the firmness of the assembled structure.
- 5 47. A method according to claim 45 or claim 46, wherein the sintering process causes the adhesion of the assembled structure to the substrate to increase.
48. A method according to any of the preceding claims, wherein the diameter
10 of the nanoparticles is in the range 1–500 nm.
49. A method according to any of the preceding claims, wherein the relative permittivity of the nanoparticles is different from the relative permittivity of the fluid.
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50. A method according to any of the preceding claims, wherein the nanoparticles comprise an electrically conductive material.
51. A method according to any of the preceding claims, wherein the
20 nanoparticles comprise a semiconducting material.
52. A method according to claim 51, further comprising exposing the fluid on the region to radiation having photon energy greater than or equal to the band gap of the semiconducting material.
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53. A method according to any of the preceding claims, further comprising applying a metal layer to the outside of the elongate structure by way of electrodeposition.
- 30 54. An assembly comprising a substrate having an elongate structure formed upon it, produced according to any of the preceding claims.
55. An assembly according to claim 54, wherein the substrate comprises an electrically insulating material.

56. An assembly according to claim 54 or claim 55, wherein the surface of the substrate upon which the elongate structure is formed is electrically insulating.

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57. An assembly according to any of claims 54 to 56, wherein the elongate structure has a width defined by the extent of the structure in a direction perpendicular to the elongate axis of the structure and parallel to the surface of the substrate upon which the structure is formed, and wherein the width is
10 approximately 100 nm.

58. An assembly according to any of claims 54 to 57, wherein the aspect ratio of the structure in dimensions perpendicular to the elongate axis of the structure is approximately 1.

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59. An apparatus for forming structures upon a substrate, the apparatus comprising:
a print head for depositing fluid containing electrically polarizable nanoparticles onto a substrate,
20 a first electrode and a second electrode for applying an alternating electric field to a wetted region defined by fluid deposited by the print head, and
a fluid removal device for removing deposited fluid from the substrate.

60. An apparatus according to claim 59, wherein the fluid removal device
25 comprises a heater.

61. An apparatus according to claim 59, wherein the heater comprises a radiative heating unit arranged to direct radiant heat upon a region of deposited fluid proximal to the print head.

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62. An apparatus according to any of claims 59 to 61, wherein the second electrode is moveable with respect to the first electrode.

63. An apparatus according to any of claims 59 to 62, wherein at least one of the electrodes has an elongate shape comprising a pointed end.

64. An apparatus according to any of claims 59 to 63, wherein the second
5 electrode comprises a conduit for delivering the fluid to the substrate from the print head.

65. An apparatus according to any of claims 59 to 64, wherein the second
10 electrode is formed as part of the print head.

66. An apparatus according to any of claims 59 to 65, further comprising a
signal controller configured to control an alternating electrical signal to the first
and second electrodes so as to apply an alternating electric field between the
first and second electrodes.

67. An apparatus according to claim 66, wherein the signal controller is
15 configured such that the current has an AC amplitude in the range 1–10,000 μA
and a DC bias in the range 0.1–1,000.0 μA .

68. An apparatus according to any of claims 59 to 67, further comprising a
20 mechanism for moving the print head.

69. An apparatus according to claim 68, wherein the mechanism is
configured to move the print head in an X-Y plane substantially coplanar with the
25 surface of the region of the substrate upon which the structures are to be
formed.

70. An apparatus according to claim 68 or claim 69, wherein the mechanism
is configured to move the print head in a Z direction substantially perpendicular
30 to the surface of the region of the substrate upon which the structures are to be
formed.

71. An apparatus according to any of claims 68 to 70, further comprising a
print controller for controlling the movement of the print head.

72. An apparatus according to any of claims 59 to 71, further comprising a distance sensor configured to output a distance signal comprising an indication of the distance between the print head and the substrate.

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73. An apparatus according to claim 72 when dependent on claim 71, wherein the print controller is configured to receive the distance signal and to control the movement of the print head in accordance with the distance signal so as to maintain an optimum distance between the print head and the substrate.

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74. An apparatus according to any of claims 59 to 73, further comprising a reservoir for containing the fluid.

75. An apparatus according to any of claims 59 to 74, further comprising an
15 image sensor configured to capture an image of the print head.