

1 DROPLET EJECTOR

2

3 Field of the invention

4

5 The invention relates to droplet ejectors for printheads, printheads comprising droplet
6 ejectors, printers comprising printheads comprising droplet ejectors and methods for
7 actuating droplet ejectors for printheads.

8

9 Background to the invention

10

11 Inkjet printers are used to recreate digital images on a print medium (such as paper)
12 by propelling droplets of ink onto the medium. Many inkjet printers incorporate "drop
13 on demand" technology wherein the sequential ejection of individual ink droplets from
14 the inkjet nozzle of a printhead is controlled. The ink droplets are ejected with sufficient
15 momentum that they adhere to the medium. Each droplet is ejected according to an
16 applied drive signal, which differentiates drop on demand inkjet printers from
17 continuous inkjet devices where a continuous stream of ink droplets is generated by
18 pumping ink through a microscopic nozzle.

19

20 Two of the most commercially successful drop on demand technologies are thermal
21 inkjet printers and piezoelectric inkjet printers. Thermal inkjet printers require the
22 printing fluid to include a volatile component, such as water. A heating element causes
23 the spontaneous nucleation of a bubble in the volatile fluid within the printhead, forcing
24 a droplet of fluid to be ejected through a nozzle. Piezoelectric inkjet printers instead

1 incorporate a piezoelectric actuator into a wall of a fluid chamber. Deformation of a
2 piezoelectric element causes deflection of the piezoelectric actuator, inducing a
3 pressure change in the printing fluid stored within the fluid chamber and thereby
4 causing droplet ejection through a nozzle.

5
6 Thermal inkjet printers can only be used to jet a very small subset of printing fluids (as
7 the fluids must exhibit the appropriate volatility). Thermal inkjet printers also suffer
8 from kogation, wherein dried ink residue deposits on the heating element, which
9 reduces their usable lifetime.

10
11 Piezoelectric inkjet printers are usable with a range of fluids and have longer
12 operational lifetimes than thermal inkjet printers, because they do not suffer from
13 kogation. However, only very low nozzle counts per printhead are typically achievable
14 with existing piezoelectric technologies compared to thermal inkjet printheads.

15
16 Aspects of the present invention aim to provide an improved piezoelectric droplet
17 ejector for a printhead which permits higher nozzle counts to be achieved.

18 19 Summary of the invention

20
21 A first aspect of the invention provides a droplet ejector for a printhead. The droplet
22 ejector comprises: a substrate having a mounting surface and an opposite nozzle
23 surface; a nozzle-forming layer formed on at least a portion of the nozzle surface of the
24 substrate; and a fluid chamber defined at least in part by the substrate and at least in
25 part by the nozzle-forming layer. The fluid chamber has a fluid chamber outlet defined
26 at least in part by a nozzle portion of the said nozzle-forming layer.

27
28 The nozzle portion of the nozzle-forming layer typically functions as (e.g. forms or is) a
29 diaphragm for ejecting fluid from the fluid chamber through the fluid chamber outlet.
30 The diaphragm is typically movable. The diaphragm is typically flexible. Movement
31 (e.g. flexing) of the diaphragm towards (i.e. into) the fluid chamber typically causes
32 expulsion of fluid through the fluid chamber outlet.

33
34 The droplet ejector typically further comprises at least one actuator arrangement (e.g.
35 one or more actuators) formed on at least a portion of the nozzle portion of the nozzle-
36 forming layer (e.g. the diaphragm). The at least one actuator arrangement (e.g. the

1 one or more actuators) is typically configured (e.g. positioned) to (i.e. in use) move or
2 flex the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) on actuation.

3
4 The at least one actuator arrangement (e.g. the one or more actuators) may comprise
5 (e.g. consist of) an inner actuator arrangement (e.g. one or more inner actuators). The
6 inner actuator arrangement (e.g. the one or more inner actuators) is typically an
7 actuator arrangement formed on at least a portion of the nozzle portion of the nozzle-
8 forming layer (e.g. the diaphragm) adjacent the fluid chamber outlet. That is to say,
9 the inner actuator arrangement (e.g. the one or more inner actuators) is typically an
10 actuator arrangement formed on at least a portion of the nozzle portion of the nozzle-
11 forming layer (e.g. the diaphragm) which is closer to the fluid chamber outlet than a
12 periphery (e.g. outer perimeter) of the nozzle portion of the nozzle-forming layer (e.g.
13 the diaphragm).

14
15 The at least one actuator arrangement (e.g. the one or more actuators) may comprise
16 (e.g. consist of) an outer actuator arrangement (e.g. one or more outer actuators). The
17 outer actuator arrangement (e.g. the one or more outer actuators) is typically an
18 actuator arrangement formed on at least a portion of the nozzle portion of the nozzle-
19 forming layer (e.g. the diaphragm) adjacent the periphery (e.g. outer perimeter) of the
20 nozzle portion of the nozzle-forming layer (e.g. the diaphragm). That is to say, the
21 outer actuator arrangement (e.g. the one or more outer actuators) is typically an
22 actuator arrangement formed on at least a portion of the nozzle portion of the nozzle-
23 forming layer (e.g. the diaphragm) which is closer to the periphery (e.g. outer perimeter)
24 of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) than the fluid
25 chamber outlet.

26
27 It may be that the droplet ejector comprises both an inner actuator arrangement (e.g.
28 one or more inner actuators) and an outer actuator arrangement (e.g. one or more
29 outer actuators). Alternatively, it may be that the droplet ejector comprises an inner
30 actuator arrangement (e.g. one or more inner actuators) or an outer actuator
31 arrangement (e.g. one or more outer actuators) but not both. That is to say, the
32 presence of an inner actuator arrangement (e.g. one or more inner actuators) does not
33 necessarily imply the presence of an outer actuator arrangement (e.g. one or more
34 outer actuators) and, vice versa, the presence of an outer actuator arrangement (e.g.
35 one or more outer actuators) does not necessarily imply the presence of an inner
36 actuator arrangement (e.g. one or more inner actuators).

37

1 The nozzle portion of the nozzle-forming layer (e.g. the diaphragm) typically comprises
2 (e.g. consists of) an inner portion and an outer portion.

3

4 The inner portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm)
5 is typically a portion of the nozzle portion located adjacent the fluid chamber outlet.
6 The inner portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm)
7 is typically a portion of the nozzle portion located closer to the fluid chamber outlet than
8 to the periphery (e.g. outer perimeter) of the nozzle portion of the nozzle-forming layer
9 (e.g. the diaphragm). The inner portion of the nozzle portion of the nozzle-forming layer
10 (e.g. the diaphragm) may be a portion of the nozzle portion which abuts (i.e. extend up to)
11 to the fluid chamber outlet. The inner portion of the nozzle portion of the nozzle-
12 forming layer (e.g. the diaphragm) may be a portion of the nozzle portion which at least
13 partially surrounds the fluid chamber outlet. The inner portion of the nozzle portion of
14 the nozzle-forming layer (e.g. the diaphragm) may be a portion of the nozzle portion
15 which completely surrounds the fluid chamber outlet. The inner portion of the nozzle
16 portion of the nozzle-forming layer (e.g. the diaphragm) may be a portion of the nozzle
17 portion which comprises the fluid chamber outlet (i.e. the fluid chamber outlet may
18 extend through the inner portion of the nozzle portion of the nozzle-forming layer (e.g.
19 the diaphragm).

20

21 The outer portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm)
22 is typically a portion of the nozzle portion provided adjacent the periphery (e.g. outer
23 perimeter) of the nozzle portion of the nozzle-forming layer (e.g. diaphragm). The outer
24 portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) is typically
25 a portion of the nozzle portion provided closer to the periphery (e.g. outer perimeter) of
26 the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) than the fluid
27 chamber outlet. The outer portion of the nozzle portion of the nozzle-forming layer (e.g.
28 the diaphragm) may be a portion of the nozzle portion which abuts (i.e. extend up to)
29 the inner portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm).
30 The outer portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm)
31 is typically a portion of the nozzle portion provided at least partially around the inner
32 portion of said nozzle portion of the nozzle-forming layer (e.g. the diaphragm). The
33 outer portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) may
34 be a portion of the nozzle portion which at least partially surrounds the inner portion of
35 the nozzle portion of the nozzle-forming layer (e.g. the diaphragm). The outer portion
36 of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) may be a portion
37 of the nozzle portion which completely surrounds the inner portion of the nozzle portion

1 of the nozzle-forming layer (e.g. the diaphragm). The outer portion of the nozzle portion
2 of the nozzle-forming layer (e.g. the diaphragm) may be a portion of the nozzle portion
3 which abuts (i.e. extend up to) the periphery (e.g. outer perimeter) of the nozzle portion
4 of the nozzle-forming layer (e.g. the diaphragm). The outer portion of the nozzle portion
5 of the nozzle-forming layer (e.g. the diaphragm) may be a portion of the nozzle portion
6 which extends between the inner portion of the nozzle portion of the nozzle-forming
7 layer (e.g. the diaphragm) and the periphery (e.g. outer perimeter) of the nozzle portion
8 of the nozzle-forming layer (e.g. the diaphragm).

9
10 The inner portion of the nozzle portion of the nozzle-forming layer is typically a portion
11 of the nozzle-forming layer which is curved on actuation. The outer portion of the
12 nozzle portion of the nozzle-forming layer is typically a portion of the nozzle-forming
13 layer which is curved on actuation. The said outer and inner portions typically curve in
14 opposite directions (i.e. face in opposite directions) when curved on actuation.
15 Accordingly, when viewed from one direction (e.g. from a point outside the fluid
16 chamber), one of the inner portion and the outer portion typically appears incurvate and
17 the other of the inner portion and the outer portion typically appears excurve on
18 actuation.

19
20 It may be that the at least one actuator arrangement (e.g. the at least one inner and/or
21 outer actuator arrangement) and the nozzle portion of the nozzle-forming layer are
22 configured such that the inner portion of the nozzle portion curves in a first sense and
23 the outer portion of the nozzle portion curves in a second sense opposite said first
24 sense (i.e. on activation).

25
26 Together, the inner and outer portions of the nozzle portion of the nozzle-forming layer
27 (e.g. diaphragm) may form the entire nozzle portion of the nozzle-forming layer (e.g.
28 diaphragm).

29
30 It may be that the inner portion is an inner half of the nozzle portion and the outer
31 portion is an outer half of the nozzle portion. A boundary between the inner and outer
32 portions may extend around the fluid chamber outlet approximately 50% of the distance
33 between the fluid chamber outlet and the outer periphery of the nozzle portion.

34
35 It may be that the inner portion comprises approximately 50% of the surface area of
36 the nozzle portion. It may be that the outer portion comprises approximately 50% of
37 the surface area of the nozzle portion. It may be that the inner portion comprises less

1 than 50% of the surface area of the nozzle portion and that the outer portion comprises
2 more than 50% of the surface area of the nozzle portion (the areas of the inner and
3 outer portions together typically making up the total surface area of the nozzle portion).
4 It may be that the inner portion comprises approximately 25% of the surface area of
5 the nozzle portion and that the outer portion comprises approximately 75% of the
6 surface area of the nozzle portion (the areas of the inner and outer portions together
7 typically making up the total surface area of the nozzle portion).

8
9 The inner and outer portions of the nozzle portion of the nozzle-forming layer (e.g. the
10 diaphragm) may be coaxially arranged. The inner and outer portions of the nozzle
11 portion of the nozzle-forming layer (e.g. the diaphragm) may be concentrically
12 arranged. The inner and outer portions of the nozzle portion of the nozzle-forming layer
13 (e.g. the diaphragm) may be geometrically similar to each other. The inner and outer
14 portions of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) may
15 each be geometrically similar to the nozzle portion of the nozzle-forming layer (e.g.
16 diaphragm). The inner and outer portions of the nozzle portion of the nozzle-forming
17 layer (e.g. the diaphragm) may be coaxially (e.g. concentrically) arranged around the
18 fluid chamber outlet.

19
20 It may be that the inner and outer portions of the nozzle portion of the nozzle-forming
21 layer (e.g. the diaphragm) each extend along approximately 50% of the width
22 (measured in cross-section along a principal axis of the nozzle portion of the nozzle-
23 forming layer (e.g. the diaphragm) in the plane of said nozzle-forming layer (e.g. the
24 diaphragm)) of the nozzle portion of the nozzle-forming layer (e.g. diaphragm). For
25 example, it may be that the nozzle portion of the nozzle-forming layer (e.g. the
26 diaphragm) is substantially circular (e.g. annular), that each of the inner and outer
27 portions of the nozzle-forming layer (e.g. diaphragm) are substantially annular and
28 concentrically arranged, the outer portion extending around the inner portion, the inner
29 portion having an external radius approximately 50% of the external radius of the
30 nozzle portion of the nozzle-forming layer (e.g. the diaphragm) and the outer portion
31 having an internal radius approximately 50% of the external radius of the nozzle portion
32 of the nozzle-forming layer (e.g. the diaphragm) and an external radius approximately
33 equal to the external radius of the nozzle portion of the nozzle-forming layer (e.g. the
34 diaphragm).

35
36 The inner actuator arrangement (e.g. the one or more inner actuators), where present,
37 is typically an actuator arrangement (e.g. one or more actuators) formed on the inner

1 portion of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm). The outer
2 actuator arrangement (e.g. the one or more outer actuators), where present, is typically
3 an actuator arrangement (e.g. one or more actuators) formed on the outer portion of
4 the nozzle portion of the nozzle-forming layer (e.g. the diaphragm).

5
6 It may be that the droplet ejector comprises only an inner actuator arrangement (e.g.
7 one or more inner actuators) and that the droplet ejector does not comprise an outer
8 actuator arrangement (e.g. one or more outer actuators). That is to say, it may be that
9 the droplet ejector comprises at least one actuator arrangement (e.g. at least one
10 actuator) formed on the inner portion of the nozzle portion of the nozzle-forming layer
11 (e.g. the diaphragm) and that the droplet ejector does not comprise any actuator
12 arrangement (e.g. actuator) formed on the outer portion of the nozzle portion of the
13 nozzle-forming layer (e.g. the diaphragm).

14
15 Alternatively, it may be that the droplet ejector comprises only an outer actuator
16 arrangement (e.g. one or more outer actuators) and that the droplet ejector does not
17 comprise an inner actuator arrangement (e.g. one or more inner actuators). That is to
18 say, it may be that the droplet ejector comprises at least one actuator arrangement
19 (e.g. at least one actuator) formed on the outer portion of the nozzle portion of the
20 nozzle-forming layer (e.g. the diaphragm) and that the droplet ejector does not
21 comprise any actuator arrangement (e.g. actuator) formed on the inner portion of the
22 nozzle portion of the nozzle-forming layer (e.g. the diaphragm).

23
24 It may be that the inner actuator arrangement (e.g. the one or more inner actuators) is
25 formed on less than 50%, or more typically less than 40%, or more typically less than
26 30%, of the nozzle portion of the nozzle-forming layer which deforms on actuation.

27
28 It may be that the outer actuator arrangement (e.g. the one or more outer actuators) is
29 formed on less than 50%, or more typically less than 40%, or more typically less than
30 30%, of the nozzle portion of the nozzle-forming layer which deforms on actuation.

31
32 The inventor has found that, surprisingly, the provision of only an inner actuator
33 arrangement or only an outer actuator arrangement enables droplet ejection efficiency
34 to be increased compared to known droplet ejectors in which a single actuator
35 arrangement is provided across the majority (e.g. all of) the nozzle portion of the
36 nozzle-forming layer (i.e. overlapping both inner and outer portions of the said nozzle
37 portion of the nozzle-forming layer).

1
2 For example, in embodiments in which the droplet ejector comprises only an inner
3 actuator arrangement (e.g. one or more inner actuators), the droplet ejector typically
4 functions, in use, by actuation of the said inner actuator arrangement to drive direct
5 deflection of the inner portion of the nozzle portion of the nozzle-forming layer in a first
6 direction (e.g. first sense). Because the nozzle portion of the nozzle-forming layer is
7 typically fixed in position at its periphery (i.e. outer perimeter), deflection of the inner
8 portion of the nozzle portion of the nozzle-forming layer in the first direction (e.g. first
9 sense) typically causes compensatory deflection of the outer portion of the nozzle
10 portion of the nozzle-forming layer in a second direction (e.g. second sense) opposite
11 the first direction. Deflection of the nozzle portion of the nozzle-forming layer towards
12 (i.e. into) the fluid chamber typically causes ejection of printing fluid from the fluid
13 chamber through the fluid chamber outlet. Because the actuator arrangement is only
14 provided on the inner portion, on actuation the nozzle portion is deformed with greater
15 volumetric deflection (for example, by forming a more complex shape) than is achieved
16 if a single actuator arrangement is provided across the majority (e.g. all of) the nozzle
17 portion of the nozzle-forming layer as is known in the art. In particular, the inventor has
18 found that it is possible to deform the nozzle portion into shapes (and particularly
19 shapes having sigmoidal cross-sections) which permit a much greater ejection force to
20 be exerted than is possible with existing droplet ejectors using similar materials. This
21 increased ejection force enables a more efficient configuration of the actuator (and, for
22 example, the use of individually less powerful actuators than are normally used in inkjet
23 printers and, in the case of piezoelectric droplet ejectors, the use of different
24 piezoelectric materials).

25
26 Similarly, in embodiments in which the droplet ejector comprises only an outer actuator
27 arrangement (e.g. one or more outer actuators), geometric constraints ensure that the
28 nozzle portion of the nozzle-forming layer deforms with greater volumetric deflection
29 (for example, by forming more complex shapes) (than are possible using existing
30 devices) on actuation of the outer actuator arrangement.

31
32 In alternative embodiments, it may be that the droplet ejector comprises at least one
33 inner actuator arrangement (e.g. one or more inner actuators) and at least one outer
34 actuator arrangement (e.g. one or more outer actuators). That is to say, it may be that
35 the droplet ejector comprises at least one (i.e. inner) actuator arrangement (e.g. one or
36 more actuators) formed on at least a portion (e.g. the inner portion) of the nozzle portion
37 of the nozzle-forming layer (e.g. the diaphragm) and at least one (i.e. outer) actuator

1 arrangement (e.g. one or more actuators) formed on at least a portion (e.g. the outer
2 portion) of the nozzle portion of the nozzle-forming layer (e.g. the diaphragm) at least
3 partially surrounding the inner actuator arrangement.

4
5 In embodiments comprising both inner and outer actuator arrangements, actuation of
6 the inner actuator arrangement typically causes deflection of the inner portion of the
7 nozzle portion of the nozzle-forming layer in a first direction (e.g. first sense) and
8 actuation of the outer actuator arrangement typically causes deflection of the outer
9 portion of the nozzle portion of the nozzle-forming layer in a second direction (e.g.
10 second sense), typically opposite said first direction (e.g. first sense). Deflection of
11 both the inner and outer portions of the nozzle portion of the nozzle-forming layer
12 typically causes ejection of printing fluid from the fluid chamber through the fluid
13 chamber outlet. Because the droplet ejector comprises both the inner actuator
14 arrangement and the outer actuator arrangement, it is possible to drive deflection of
15 both the inner and outer portions of the nozzle portion of the nozzle-forming layer (for
16 example, at the same time). Again, the nozzle portion can be deformed with greater
17 volumetric deflection (for example, by forming more complex shapes) than are
18 achievable if only a single actuator arrangement is provided on the nozzle portion of
19 the nozzle-forming layer (and particularly a single actuator arrangement which extends
20 across a majority of the nozzle portion of the nozzle-forming layer, e.g. overlapping
21 both the inner and outer portions of said nozzle portion). In particular, the inventor has
22 found that concurrent actuation of both the inner and outer actuator arrangements can
23 be used to deform the nozzle portion into shapes which permit a greater ejection force
24 to be exerted on the printing fluid. Again, this enables a more efficient configuration of
25 the actuator (and, for example, use of individually less powerful actuators than are
26 normally used in inkjet printers).

27
28 It may be that the droplet ejector comprises at least one electronic component
29 integrated with the substrate. The at least one electronic component may comprise at
30 least one active electronic component (e.g. a transistor). Additionally or alternatively,
31 the at least one electronic component may comprise at least one passive electronic
32 component (e.g. a resistor). The at least one electronic component may comprise at
33 least one CMOS (i.e. complementary metal-oxide-semiconductor) electronic
34 component integrated with the substrate.

35
36 In embodiments comprising an inner actuator arrangement (i.e. irrespective of the
37 presence or lack of an outer actuator arrangement), the inner actuator arrangement

1 typically at least partially surrounds the fluid chamber outlet. That is to say, the inner
2 actuator arrangement is typically formed on the inner portion of the nozzle portion of
3 the nozzle-forming layer at least partially surrounding the fluid chamber outlet. It may
4 be that the inner actuator arrangement surrounds the fluid chamber outlet. It may be
5 that the inner actuator arrangement completely surrounds the fluid chamber outlet. It
6 may be that the inner actuator arrangement extends continuously around the fluid
7 chamber outlet.

8
9 It may be that the inner actuator arrangement consists of a single inner actuator.

10
11 It may be that the inner actuator arrangement comprises two or more inner actuators,
12 each of which partially surrounds the fluid chamber outlet. The two or more inner
13 actuators are typically spaced apart from one another. The two or more inner actuators
14 are typically spaced apart from one another around the fluid chamber outlet (i.e. rather
15 than being radially spaced apart from one another). Accordingly, it may be that the
16 inner actuator arrangement extends discontinuously around the fluid chamber outlet.

17
18 It may be that the inner actuator arrangement is substantially annular (i.e. ring-shaped).
19 It may be that inner actuator arrangement is centred on the fluid chamber outlet. It
20 may be that the inner actuator arrangement comprises two or more substantially
21 annular inner actuators. It may be that the inner actuator arrangement comprises two
22 or more inner actuators each being partially annular in shape (i.e. each shaped so as
23 to form a portion (e.g. a sector) of an annulus (i.e. a portion of a ring)). It may be that
24 the two or more partially annular inner actuators are centred on (i.e. arranged
25 symmetrically around) the fluid chamber outlet.

26
27 By providing the droplet ejector with substantially annular actuator arrangements
28 centred on the fluid chamber outlet, deflection of the nozzle portion of the nozzle-
29 forming layer is typically uniform (i.e. symmetric) around the fluid chamber outlet,
30 resulting in smooth expulsion of droplets from the fluid chamber outlet.

31
32 It may be that the inner actuator arrangement is a piezoelectric actuator arrangement,
33 e.g. an inner piezoelectric actuator arrangement.

34
35 It may be that the inner actuator arrangement (i.e. the inner piezoelectric actuator
36 arrangement) comprises one or more inner piezoelectric actuators.

37

1 At least one of the one or more inner piezoelectric actuators typically comprises a
2 piezoelectric body (i.e. an inner piezoelectric body) provided between a pair of drive
3 electrodes (i.e. an inner pair of drive electrodes).

4
5 It may be that each of the one or more inner piezoelectric actuators comprises a
6 piezoelectric body provided between a corresponding pair of drive electrodes (i.e. an
7 inner piezoelectric body provided between a corresponding inner pair of drive
8 electrodes).

9
10 It may be that the inner piezoelectric actuator arrangement is substantially annular (i.e.
11 ring-shaped). It may be that the inner piezoelectric actuator arrangement is centred on
12 the fluid chamber outlet.

13
14 It may be that the inner actuator arrangement consists of a single inner piezoelectric
15 actuator. It may be that the single inner piezoelectric actuator is substantially annular.
16 It may be that the single inner piezoelectric actuator is centred on the fluid chamber
17 outlet.

18
19 It may be that the inner actuator arrangement comprises two or more inner
20 piezoelectric actuators. It may be that the inner actuator arrangement comprises two
21 or more substantially annular inner piezoelectric actuators. It may be that the inner
22 actuator arrangement comprises two or more inner piezoelectric actuators each being
23 partially annular in shape (i.e. each shaped so as to form a portion (e.g. a sector) of an
24 annulus (i.e. a portion of a ring)). It may be that the two or more partially annular inner
25 piezoelectric actuators are centred on (i.e. arranged symmetrically around) the fluid
26 chamber outlet.

27
28 It may be that the inner piezoelectric actuators are formed from portions of the same
29 continuous inner piezoelectric body. However, each of the inner piezoelectric
30 actuators typically comprises its own respective pair of inner drive electrodes.

31
32 It may be that the inner piezoelectric body does not extend into the outer portion of the
33 nozzle portion of the nozzle-forming layer.

34
35 It may be that the nozzle portion of the nozzle-forming layer comprises an inner portion
36 and an outer portion, and an inner piezoelectric actuator arrangement formed on the
37 inner portion, wherein the outer portion has no piezoelectric actuator arrangement

1 formed thereon, wherein actuation of the inner piezoelectric actuator arrangement
2 deforms the inner portion in a first sense (i.e. first direction) by virtue of the forces
3 directly applied to the said inner portion by the said inner piezoelectric actuator
4 arrangement, and wherein the outer portion deforms in a second opposite sense (i.e.
5 second opposite direction) by virtue of being connected to the inner portion and being
6 held around a periphery of said outer portion.

7
8 The inner piezoelectric actuator arrangement is typically formed on less than 50%, or
9 more typically less than 40%, or more typically less than 30% of the surface area of the
10 nozzle portion which deforms during operation (i.e. on actuation of said inner
11 piezoelectric actuator arrangement).

12
13 It may be that the inner pair of drive electrodes is electrically connected to a drive
14 circuit. The drive circuit is typically configured to selectively apply (i.e. when actuated
15 (e.g. when in use, connected to a power supply (e.g. a voltage signal line) and
16 responsive to an actuation signal)) a potential difference between the inner pair of drive
17 electrodes to cause deflection of the inner piezoelectric body.

18
19 It may be that one or more electrodes of the inner pair of drive electrodes are electrically
20 connected to the at least one electronic component integrated with the substrate.

21
22 In embodiments comprising an outer actuator arrangement (i.e. irrespective of the
23 presence or lack of an inner actuator arrangement), the outer actuator arrangement
24 typically at least partially surrounds the fluid chamber outlet. That is to say, the outer
25 actuator arrangement is typically formed on the outer portion of the nozzle portion of
26 the nozzle-forming layer at least partially surrounding the fluid chamber outlet.

27
28 It may be that the outer actuator arrangement surrounds the fluid chamber outlet. It
29 may be that the outer actuator arrangement completely surrounds the fluid chamber
30 outlet. It may be that the outer actuator arrangement extends continuously around the
31 fluid chamber outlet.

32
33 It may be that the outer actuator arrangement consists of a single outer actuator.

34
35 It may be that the outer actuator arrangement comprises two or more outer actuators,
36 each of which partially surrounds the fluid chamber outlet. The two or more outer
37 actuators are typically spaced apart from one another around the fluid chamber outlet

1 (i.e. rather than being radially spaced apart). Accordingly, it may be that the outer
2 actuator arrangement extends discontinuously around the fluid chamber outlet.

3
4 It may be that the outer actuator arrangement is substantially annular (i.e. ring-shaped).
5 It may be that outer actuator arrangement is centred on the fluid chamber outlet. It
6 may be that the outer actuator arrangement comprises two or more substantially
7 annular outer actuators. It may be that the outer actuator arrangement comprises two
8 or more outer actuators each being partially annular in shape (i.e. each shaped so as
9 to form a portion (e.g. a sector) of an annulus (i.e. a portion of a ring)). It may be that
10 the two or more partially annular outer actuators are centred on (i.e. arranged
11 symmetrically around) the fluid chamber outlet.

12
13 By providing the droplet ejector with substantially annular actuator arrangements
14 centred on the fluid chamber outlet, deflection of the nozzle portion of the nozzle-
15 forming layer is typically uniform (i.e. symmetric) around the fluid chamber outlet,
16 resulting in smooth expulsion of droplets from the fluid chamber outlet.

17
18 It may be that the outer actuator arrangement is a piezoelectric actuator arrangement,
19 e.g. an outer piezoelectric actuator arrangement.

20
21 It may be that the outer actuator arrangement (i.e. the outer piezoelectric actuator
22 arrangement) comprises one or more outer piezoelectric actuators.

23
24 At least one of the one or more outer piezoelectric actuators typically comprises a
25 piezoelectric body (i.e. an outer piezoelectric body) provided between a pair of drive
26 electrodes (i.e. an outer pair of drive electrodes).

27
28 It may be that each of the one or more outer piezoelectric actuators comprises a
29 piezoelectric body provided between a corresponding pair of drive electrodes (i.e. an
30 outer piezoelectric body provided between a corresponding outer pair of drive
31 electrodes).

32
33 It may be that the outer piezoelectric actuator arrangement is substantially annular (i.e.
34 ring-shaped). It may be that the outer piezoelectric actuator arrangement is centred
35 on the fluid chamber outlet.

36

1 It may be that the outer actuator arrangement consists of a single outer piezoelectric
2 actuator. It may be that the single outer piezoelectric actuator is substantially annular.
3 It may be that the single outer piezoelectric actuator is centred on the fluid chamber
4 outlet.

5
6 It may be that the outer actuator arrangement comprises two or more outer
7 piezoelectric actuators. It may be that the outer actuator arrangement comprises two
8 or more substantially annular outer piezoelectric actuators. It may be that the outer
9 actuator arrangement comprises two or more outer piezoelectric actuators each being
10 partially annular in shape (i.e. each shaped so as to form a portion (e.g. a sector) of an
11 annulus (i.e. a portion of a ring)). It may be that the two or more partially annular outer
12 piezoelectric actuators are centred on (i.e. arranged symmetrically around) the fluid
13 chamber outlet.

14
15 It may be that the outer piezoelectric actuators are formed from portions of the same
16 continuous outer piezoelectric body. However, each of the outer piezoelectric
17 actuators typically comprises its own respective pair of outer drive electrodes.

18
19 It may be that the outer piezoelectric body does not extend into the inner portion of the
20 nozzle portion of the nozzle-forming layer.

21
22 It may be that the nozzle portion of the nozzle-forming layer comprises an outer portion
23 and an inner portion, and an outer piezoelectric actuator arrangement formed on the
24 outer portion, wherein the inner portion has no piezoelectric actuator arrangement
25 formed thereon, wherein actuation of the outer piezoelectric actuator arrangement
26 deforms the outer portion in a first sense (i.e. first direction) by virtue of the forces
27 directly applied to the said outer portion by the said outer piezoelectric actuator
28 arrangement, and wherein the inner portion deforms in a second opposite sense (i.e.
29 second opposite direction) by virtue of being connected to and retained within the outer
30 portion.

31
32 The outer piezoelectric actuator arrangement is typically formed on less than 50%, or
33 more typically less than 40%, or more typically less than 30% of the surface area of the
34 nozzle portion which deforms during operation (i.e. on actuation of said outer
35 piezoelectric actuator arrangement).

36

1 It may be that the outer pair of drive electrodes is electrically connected to a drive circuit
2 (e.g. the drive circuit to which the inner pair of drive electrodes is connected, where
3 present). The drive circuit is typically configured to selectively apply (i.e. when
4 actuated (e.g. when in use, connected to a power supply (e.g. a voltage signal line)
5 and responsive to an actuation signal)) a potential difference between the outer pair of
6 drive electrodes to cause deflection of the outer piezoelectric body.

7
8 It may be that one or more electrodes of the outer pair of drive electrodes are
9 electrically connected to the at least one electronic component integrated with the
10 substrate.

11
12 In embodiments comprising both inner and outer actuator arrangements, the outer
13 actuator arrangement typically at least partially surrounds the inner actuator
14 arrangement. That is to say, the outer actuator arrangement is typically formed on the
15 outer portion of the nozzle portion of the nozzle-forming layer at least partially
16 surrounding the inner actuator arrangement formed on the inner portion of the nozzle
17 portion of the nozzle-forming layer.

18
19 It may be that the outer actuator arrangement surrounds the inner actuator
20 arrangement. It may be that the outer actuator arrangement completely surrounds the
21 inner actuator arrangement. It may be that the outer actuator arrangement extends
22 continuously around the inner actuator arrangement.

23
24 It may be that the outer actuator arrangement comprises two or more outer actuators,
25 each of which partially surrounds the inner actuator arrangement. The two or more
26 outer actuators are typically spaced apart from one another around the inner actuator
27 arrangement. Accordingly, it may be that the outer actuator arrangement extends
28 discontinuously around the inner actuator arrangement.

29
30 The inner actuator arrangement is typically provided closer (i.e. than the outer actuator
31 arrangement) to the fluid chamber outlet (e.g. to a periphery of the fluid chamber outlet)
32 and the outer actuator arrangement is typically provided further away (i.e. than the
33 inner actuator arrangement) from the fluid chamber outlet (e.g. from the periphery of
34 the fluid chamber outlet).

35
36 The outer actuator arrangement is typically spaced apart (i.e. radially) from the inner
37 actuator arrangement.

1
2 It may be that both the inner and outer actuator arrangements are centred on the fluid
3 chamber outlet. It may be that the inner and outer actuator arrangements are coaxially
4 arranged. It may be that the inner and outer actuator arrangements are co-centric. It
5 may be that both the inner and outer actuator arrangements are formed symmetrically
6 around the fluid chamber outlet. It may be that both the inner and outer actuator
7 arrangements are concentrically arranged.

8
9 By providing the droplet ejector with substantially annular actuator arrangements
10 centred on the fluid chamber outlet, deflection of the nozzle portion of the nozzle-
11 forming layer is typically uniform (i.e. symmetric) around the fluid chamber outlet,
12 resulting in smooth expulsion of droplets from the fluid chamber outlet.

13
14 It may be that the inner actuator arrangement is a piezoelectric actuator arrangement,
15 e.g. an inner piezoelectric actuator arrangement, and/or the outer actuator
16 arrangement is a piezoelectric actuator arrangement, e.g. an outer piezoelectric
17 actuator arrangement. It will be understood that by referring to the inner actuator
18 arrangement as an inner piezoelectric actuator arrangement, there is no implication
19 that the outer actuator arrangement is necessarily a piezoelectric actuator arrangement
20 (i.e. an outer piezoelectric actuator arrangement). Similarly, it will be understood that
21 by referring to the outer actuator arrangement as an outer piezoelectric actuator
22 arrangement, there is no implication that the inner actuator arrangement is necessarily
23 a piezoelectric actuator arrangement (i.e. an inner piezoelectric actuator arrangement).
24 For example, it may be that one of the inner actuator arrangement and the outer
25 actuator arrangement is a piezoelectric actuator arrangement (i.e. either an inner
26 piezoelectric actuator arrangement or an outer piezoelectric actuator arrangement)
27 and the other of the inner actuator arrangement and the outer actuator arrangement is
28 a non-piezoelectric actuator arrangement (i.e. either an outer non-piezoelectric
29 actuator arrangement or an inner non-piezoelectric actuator arrangement).
30 Alternatively, it may be that both the inner and outer actuator arrangements are
31 piezoelectric actuator arrangements (i.e. an inner piezoelectric actuator arrangement
32 and an outer piezoelectric actuator arrangement).

33
34 It may be that the inner actuator arrangement (e.g. the inner piezoelectric actuator
35 arrangement) comprises one or more inner piezoelectric actuators and the outer
36 actuator arrangement (e.g. the outer piezoelectric actuator arrangement) comprises
37 one or more outer piezoelectric actuators. Typically, the one or more outer

1 piezoelectric actuators at least partially surround the one or more inner piezoelectric
2 actuators.

3

4 It may be that each of the one or more inner piezoelectric actuators comprises a
5 piezoelectric body provided between a corresponding pair of drive electrodes (i.e. an
6 inner piezoelectric body provided between a corresponding inner pair of drive
7 electrodes). It may be that each of the one or more outer piezoelectric actuators
8 comprises a piezoelectric body provided between a corresponding pair of drive
9 electrodes (i.e. an outer piezoelectric body provided between a corresponding outer
10 pair of drive electrodes). However, it will be understood that by referring to a
11 piezoelectric body of the inner actuator arrangement as an inner piezoelectric body,
12 there is no implication that the outer actuator arrangement necessarily comprises an
13 outer piezoelectric body (e.g. the outer actuator arrangement may be non-
14 piezoelectric). Similarly, it will be understood that by referring to a piezoelectric body
15 of the outer actuator arrangement as an outer piezoelectric body, there is no implication
16 that the inner actuator arrangement necessarily comprises an inner piezoelectric body
17 (e.g. the inner actuator arrangement may be non-piezoelectric).

18

19 It may be that both the inner and outer piezoelectric bodies are formed from portions
20 of the same continuous piezoelectric body. Alternatively, it may be that the inner and
21 outer piezoelectric bodies are separate (i.e. not continuous) piezoelectric bodies. It
22 may be that the inner and outer piezoelectric bodies are spaced apart from one
23 another.

24

25 It may be that both the inner and outer pairs of drive electrodes are electrically
26 connected to a drive circuit. The drive circuit is typically configured to selectively apply
27 (i.e. when actuated (e.g. when in use, connected to a power supply (e.g. a voltage
28 signal line) and responsive to an actuation signal)) a first potential difference between
29 the inner pair of drive electrodes to cause deflection of the inner piezoelectric body in
30 a first direction and to apply a second potential difference between the outer pair of
31 drive electrodes to cause deflection of the outer piezoelectric body in a second direction
32 opposite said first direction.

33

34 The drive circuit may be configured to, when the droplet ejector is in use and connected
35 to a power supply (e.g. a voltage signal line), apply the first potential difference between
36 the inner pair of drive electrodes to cause curvature of the inner piezoelectric body in
37 a first sense and to apply the second potential difference between the outer pair of

1 drive electrodes to cause curvature of the outer piezoelectric body in a second sense
2 opposite said first sense.

3
4 The first and second potential differences typically have similar (e.g. the same)
5 magnitudes. The first and second potential differences typically have opposing
6 polarities.

7
8 It may be that one or more electrodes of the inner pair of drive electrodes and the outer
9 pair of drive electrodes are electrically connected to the at least one electronic
10 component integrated with the substrate.

11
12 It may be that the inner piezoelectric body or bodies (where present) and/or the outer
13 piezoelectric body or bodies (where present) comprise (e.g. are formed from) one or
14 more piezoelectric materials processable at a temperature below 450°C.

15
16 Above 300°C, integrated electronic components (e.g. CMOS electronic components)
17 typically begin to degrade, impairing device operation and reducing efficiency. Above
18 450°C, integrated electronic components (e.g. CMOS electronic components) typically
19 degrade even more substantially. Use of piezoelectric materials processable at a
20 temperature below 450°C therefore permits processing of, and integration of,
21 piezoelectric actuators with electronic components (e.g. of the drive circuitry) without
22 substantial damage to the said electronic components.

23
24 It may be that the inner piezoelectric body or bodies and/or the outer piezoelectric body
25 or bodies comprise (e.g. are formed from) one or more piezoelectric materials
26 processable at a temperature below 300°C. Use of piezoelectric materials processable
27 at a temperature below 300°C permits processing of, and integration of, piezoelectric
28 actuators with electronic components (e.g. of the drive circuitry) with even less damage
29 to the said electronic components. Use of piezoelectric materials processable at a
30 temperature below 300°C typically permits a higher yield of functioning devices to be
31 achieved from large-scale manufacture of multiple fluid ejectors on a single substrate
32 (e.g. from a single substrate wafer).

33
34 By integrating piezoelectric actuators with electronic components (e.g. drive
35 electronics), the need to provide separate droplet ejector drive electronics (typically
36 provided separate to any piezoelectric printhead microchip in existing devices) is
37 reduced or removed. A large number of droplet ejectors may therefore be closely

1 integrated on one chip, increasing the nozzle count per chip, reducing the overall
2 printhead size, and permitting a higher printhead nozzle density than is achievable with
3 existing piezoelectric printheads. Other benefits associated with integration on a single
4 printhead chip include eventual manufacturing cost reductions, printer system cost
5 reductions, modularity, device reliability and printer system improvements such as
6 improved redundancy and throughput.

7
8 Piezoelectric materials which are processable below 450°C (or below 300°C) typically
9 have poorer piezoelectric properties (e.g. lower piezoelectric constants) than
10 piezoelectric materials which require processing at higher temperatures. For example,
11 a piezoelectric actuator formed from a high-temperature processable piezoelectric
12 material such as lead zirconate titanate (PZT) is able to exert a force over an order of
13 magnitude greater than a piezoelectric actuator formed from a low-temperature
14 processable piezoelectric material such as aluminium nitride (AlN), all other factors
15 being equal.

16
17 However, the inventor has found that, by providing an inner piezoelectric actuator
18 arrangement and/or an outer piezoelectric actuator arrangement, the droplet ejection
19 efficiency of the droplet ejector may be improved (in particular when compared to the
20 provision of piezoelectric actuators on a fluid chamber wall further away from the fluid
21 chamber outlet, as is found in existing piezoelectric droplet ejectors) sufficiently that
22 use of low-temperature processable piezoelectric materials becomes feasible. It is the
23 particular structure of the droplet ejector in the present invention which enables the use
24 of low-temperature processable piezoelectric materials, which itself then permits
25 integration of the droplet ejector with drive electronics.

26
27 In particular, application of an electric field (i.e. potential difference) between the inner
28 pair or pairs of drive electrodes typically induces deformation of the inner piezoelectric
29 actuator or actuators and application of an electric field (i.e. potential difference)
30 between the outer pair or pairs of drive electrodes typically induces deformation of the
31 outer piezoelectric actuator or actuators, each causing a highly damped oscillation of
32 the nozzle-portion of the nozzle-forming layer. Oscillation of the nozzle-portion of the
33 nozzle-forming layer sets up an oscillating pressure field within the fluid chamber,
34 driving ejection of a droplet through the fluid chamber outlet. By displacing the nozzle
35 portion of the nozzle-forming layer (rather than displacing a fluid chamber wall provided
36 further away from the fluid chamber outlet), relatively small fluid pressures, and thus
37 relatively small actuation forces, are required to eject a droplet of fluid, thereby

1 facilitating use of low-temperature processable piezoelectric materials having lower
2 piezoelectric constants.

3
4 Because the force exerted by piezoelectric actuators comprising low-temperature
5 processable piezoelectric materials is relatively low (compared to devices using
6 piezoelectric actuators comprising high-temperature processable piezoelectric
7 materials), and thus because relatively low fluid pressures are achieved, acoustic cross
8 talk (by way of acoustic waves propagating through the printhead) between
9 neighbouring fluid chambers on a printhead is reduced. The lower pressures reduce
10 fluidic compressibility, making acoustic cross talk less likely. Lower levels of acoustic
11 cross talk permit even closer integration of neighbouring droplet ejectors on a printhead
12 without a reduction in print quality.

13
14 Processing of a piezoelectric material typically comprises deposition of said
15 piezoelectric material. Processing of a piezoelectric material may also comprise further
16 processing of the piezoelectric material after deposition (i.e. post-deposition
17 processing, or 'post-processing', of the deposited piezoelectric material). Processing
18 of a piezoelectric material may comprise (i.e. post-deposition) annealing of the
19 piezoelectric material.

20
21 A piezoelectric material processable at a temperature below 450°C (or below 300°C)
22 is typically a piezoelectric material which is depositable at a temperature below 450°C
23 (or below 300°C). A piezoelectric material processable at a temperature below 450°C
24 (or below 300°C) does not typically require any post-deposition processing (such as
25 post-deposition annealing) at a temperature at or above 450°C (or at or above 300°C).
26 A piezoelectric material processable at a temperature below 450°C (or below 300°C)
27 is therefore typically a piezoelectric material which is annealable (after deposition) at a
28 temperature below 450°C (or below 300°C) (i.e. if annealing of the piezoelectric
29 material is required to render the piezoelectric body piezoelectric).

30
31 The one or more piezoelectric materials are typically processable (e.g. depositable
32 and, if required, annealable) at a temperature below 450°C (or below 300°C) such that
33 the piezoelectric actuators are manufacturable at a temperature below 450°C (or below
34 300°C). Manufacture of the piezoelectric actuators at a temperature below 450°C (or
35 below 300°C) typically permits integration of the piezoelectric actuators with the at least
36 one electronic component integrated with the substrate.

37

1 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
2 are therefore typically formable (e.g. by deposition and, if required, annealing of the
3 one or more piezoelectric materials) at a temperature below 450°C (or below 300°C).
4

5 The one or more piezoelectric materials are typically processable (e.g. depositable
6 and, if required, annealable) at a substrate temperature below 450°C (or below 300°C).
7 In other words, the temperature of the substrate does not typically reach or exceed
8 450°C (or 300°C) during processing (e.g. deposition and, if required, annealing) of the
9 one or more piezoelectric materials. The temperature of the substrate does not
10 typically reach or exceed 450°C (or 300°C) during formation of the piezoelectric bodies.
11 The temperature of the substrate does not typically reach or exceed 450°C (or 300°C)
12 during manufacture of the piezoelectric actuators. It may be that the temperature of
13 the substrate does not reach or exceed 450°C (or 300°C) during manufacture of the
14 (e.g. entire) droplet ejector.
15

16 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
17 are typically depositable (e.g. deposited) by one or more (e.g. low-temperature)
18 physical vapour deposition (PVD) methods. The inner piezoelectric body or bodies
19 and/or the outer piezoelectric body or bodies are typically depositable (e.g. deposited)
20 by one or more (e.g. low-temperature) physical vapour deposition methods at a
21 temperature (i.e. at a substrate temperature) below 450°C (or more preferably below
22 300°C).
23

24 It may be that inner piezoelectric body or bodies and/or the outer piezoelectric body or
25 bodies comprise (e.g. are formed from) one or more (e.g. low-temperature) PVD-
26 depositable piezoelectric materials. It may be that inner piezoelectric body or bodies
27 and/or the outer piezoelectric body or bodies comprise (e.g. are formed from) one or
28 more (e.g. low-temperature) PVD-deposited piezoelectric materials.
29

30 Physical vapour deposition methods (e.g. low-temperature physical vapour deposition
31 methods) may comprise one or more of the following deposition methods: cathodic arc
32 deposition, electron beam physical vapour deposition, evaporative deposition, pulsed
33 laser deposition, sputter deposition. Sputter deposition may comprise sputtering of
34 material from single or multiple sputtering targets.
35

36 The one or more piezoelectric materials typically have deposition temperatures below
37 450°C (or below 300°C). The one or more piezoelectric materials may have PVD-

1 deposition temperatures below 450°C (or below 300°C). The one or more piezoelectric
2 materials may have sputtering temperatures below 450°C (or below 300°C). The one
3 or more piezoelectric materials may have post-deposition annealing temperatures
4 below 450°C (or below 300°C). It will be understood that the deposition temperature,
5 the PVD-deposition temperature, the sputtering temperature or the annealing
6 temperature is typically the temperature of the substrate during the respective process.

7
8 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
9 may comprise (e.g. be formed from) one piezoelectric material. Alternatively, the inner
10 piezoelectric body or bodies and/or the outer piezoelectric body or bodies may
11 comprise (e.g. be formed from) more than one piezoelectric material.

12
13 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
14 may comprise (e.g. be formed from) a ceramic material comprising aluminium and
15 nitrogen and optionally one or more elements selected from: scandium, yttrium,
16 titanium, magnesium, hafnium, zirconium, tin, chromium, boron.

17
18 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
19 may comprise (e.g. be formed from) aluminium nitride (AlN).

20
21 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
22 may comprise (e.g. be formed from) zinc oxide (ZnO).

23
24 The one or more piezoelectric materials may comprise (e.g. consist of) aluminium
25 nitride and/or zinc oxide.

26
27 Aluminium nitride may consist of pure aluminium nitride. Alternatively, aluminium
28 nitride may comprise one or more other elements (i.e. aluminium nitride may comprise
29 aluminium nitride compounds). Aluminium nitride may comprise one or more of the
30 following elements: scandium, yttrium, titanium, magnesium, hafnium, zirconium, tin,
31 chromium, boron.

32
33 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
34 may comprise (e.g. be formed from) scandium aluminium nitride (ScAlN). The
35 percentage of scandium in scandium aluminium nitride is typically chosen to optimize
36 the d_{31} piezoelectric constant within the limits of manufacturability. For example, the
37 value of x in $\text{Sc}_x\text{Al}_{1-x}\text{N}$ is typically chosen from the range $0 < x \leq 0.5$. Greater fractions

1 of scandium typically result in larger values of d_{31} (i.e. stronger piezoelectric effects).
2 The mass percentage (i.e. the weight percentage) of scandium in scandium aluminium
3 nitride is typically greater than 5%. The mass percentage (i.e. the weight percentage)
4 of scandium in scandium aluminium nitride is typically greater than 10%. The mass
5 percentage (i.e. the weight percentage) of scandium in scandium aluminium nitride is
6 typically greater than 20%. The mass percentage (i.e. the weight percentage) of
7 scandium in scandium aluminium nitride is typically greater than 30%. The mass
8 percentage (i.e. the weight percentage) of scandium in scandium aluminium nitride is
9 typically greater than 40%. The mass percentage (i.e. the weight percentage) of
10 scandium in scandium aluminium nitride may be less than or equal to 50%.

11

12 Aluminium nitride, including aluminium nitride compounds (and in particular scandium
13 aluminium nitride), and zinc oxide are piezoelectric materials which may be deposited
14 below 450°C, or more preferably below 300°C. Aluminium nitride, including aluminium
15 nitride compounds (and in particular scandium aluminium nitride), and zinc oxide are
16 piezoelectric materials which may be deposited by physical vapour deposition (e.g.
17 sputtering) below 450°C, or more preferably below 300°C. Aluminium nitride, including
18 aluminium nitride compounds (and in particular scandium aluminium nitride), and zinc
19 oxide are piezoelectric materials which do not typically require annealing after
20 deposition.

21

22 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
23 may comprise (e.g. be formed from) aluminium nitride (e.g. aluminium nitride
24 compounds, for example scandium aluminium nitride) and/or zinc oxide deposited by
25 physical vapour deposition below 450°C, or more preferably below 300°C.

26

27 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
28 may comprise (e.g. be formed from) one or more III-V and/or II-VI semiconductors (i.e.
29 compound semiconductors comprising elements from Groups III and V and/or Groups
30 II and VI of the Periodic Table). Such III-V and II-VI semiconductors typically crystallise
31 in the hexagonal wurtzite crystal structure. III-V and II-VI semiconductors crystallising
32 in the hexagonal wurtzite crystal structure are typically piezoelectric due to their non-
33 centrosymmetric crystal structure.

34

35 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
36 may comprise (e.g. be formed from or consist of) non-ferroelectric piezoelectric
37 materials. The one or more piezoelectric materials may be one or more non-

1 ferroelectric piezoelectric materials. Ferroelectric materials typically require (i.e. post-
2 deposition) poling under strong applied electric fields. Non-ferroelectric piezoelectric
3 materials typically do not require poling.

4
5 The inner piezoelectric body or bodies and/or the outer piezoelectric body or bodies
6 typically have a piezoelectric constant d_{31} having a magnitude less than 30 pC/N, or
7 more typically less than 20 pC/N, or even more typically less than 10 pC/N. The one
8 or more piezoelectric materials typically have piezoelectric constants d_{31} having
9 magnitudes less than 30 pC/N, or more typically less than 20pC/N, or even more
10 typically less than 10 pC/N.

11
12 The one or more piezoelectric materials are typically CMOS-compatible. By this, it will
13 be understood that the one or more piezoelectric materials do not typically comprise,
14 or are typically processable (e.g. depositable, and if required, annealable) without use
15 of, substances which damage CMOS electronic structures. For example, processing
16 (e.g. deposition, and if required, annealing) of the one or more piezoelectric materials
17 does not typically include use of (e.g. strong) acids (such as hydrochloric acid) and/or
18 (e.g. strong) alkalis (such as potassium hydroxide).

19
20 It may be that the nozzle-forming layer comprises a nozzle plate. The nozzle plate may
21 consist of a single layer of material. Alternatively, the nozzle plate may consist of a
22 laminate structure of two or more layers of (e.g. different) material. The nozzle plate is
23 typically formed from one or more materials each having a Young's modulus (i.e.
24 tensile elastic modulus) of between 70 GPa and 300 GPa. The nozzle plate may be
25 formed from one or more of: silicon dioxide (SiO_2), silicon nitride (Si_3N_4), silicon carbide
26 (SiC), silicon oxynitride (SiO_xN_y).

27
28 It may be that the nozzle-forming layer comprises an electrical interconnect layer. The
29 electrical interconnect layer typically comprises one or more electrical connections
30 (e.g. electrical wiring) typically surrounded by electrical insulator. The one or more
31 electrical connections (e.g. electrical wiring) are typically formed from a metal or metal
32 alloy. Suitable metals include aluminium, copper and tungsten, and alloys thereof. The
33 electrical insulator is typically formed from a dielectric material such as silicon dioxide
34 (SiO_2), silicon nitride (Si_3N_4) or silicon oxynitride (SiO_xN_y).

35
36 It may be that the electrical interconnect layer is provided (e.g. formed) between the
37 substrate and the nozzle plate. It may be that the electrical interconnect layer is

1 provided (e.g. formed) on the second surface of the substrate, and the nozzle-plate is
2 provided (e.g. formed) on the electrical interconnect layer. The nozzle-plate may
3 comprise one or more apertures through which electrical connections to the electrical
4 interconnect layer may be formed.

5
6 It may be that a nozzle portion of the electrical interconnect layer forms at least a part
7 of the nozzle portion of the nozzle-forming layer. It may be that the nozzle portion of
8 the electrical interconnect layer consists of dielectric material. Alternatively, it may be
9 that the electrical interconnect layer does not form part of the nozzle portion of the
10 nozzle-forming layer.

11
12 The inner and outer pairs of drive electrodes typically comprise one or more layers of
13 metal (such as titanium, platinum, aluminium, tungsten, molybdenum or alloys thereof).
14 The inner and outer pairs of drive electrodes may be laminated. For example, the inner
15 and outer pairs of drive electrodes may be formed from an aluminium-molybdenum
16 (Al/Mb) laminated stack. The inner and outer pairs of drive electrodes are typically
17 deposited by (e.g. low-temperature) PVD at a temperature (i.e. at a substrate
18 temperature) below 450°C (or more typically below 300°C).

19
20 It may be that one or more of the inner and outer pairs of drive electrodes is electrically
21 connected to the at least one electronic component. It may be that each of the inner
22 and outer pairs of drive electrodes are electrically connected to the at least one
23 electronic component.

24
25 The droplet ejector may comprise the drive circuitry. Alternatively, the drive circuitry
26 may form part of a printhead comprising the droplet ejector. The drive circuitry typically
27 generates the potential differences required to operate the inner and outer actuator
28 arrangements.

29
30 The droplet ejector may comprise control circuitry. Alternatively, the control circuitry
31 may form part of a printhead comprising the droplet ejector. The control circuitry
32 typically determines when to operate the drive circuitry.

33
34 In embodiments in which the droplet ejector comprises the drive circuitry, the said drive
35 circuitry is typically integrated with the substrate. The at least one electronic
36 component typically forms part of the drive circuitry. It may be that one or more of the
37 inner and/or outer pairs of drive electrodes is connected electrically to the drive

1 circuitry. It may be that each of the inner and outer pairs of drive electrodes are
2 electrically connected to the drive circuitry.

3
4 It may be that the at least one electronic component is configured to provide a (e.g.
5 variable) potential difference (i.e. a voltage) between the inner pair or pairs of drive
6 electrodes, where present (i.e. in use). It may be that the at least one electronic
7 component is configured to vary the potential difference (i.e. voltage) between the inner
8 pair or pairs of drive electrodes (i.e. in use).

9
10 It may be that the at least one electronic component is configured to provide a (e.g.
11 variable) potential difference (i.e. a voltage) between the outer pair or pairs of drive
12 electrodes, where present (i.e. in use). It may be that the at least one electronic
13 component is configured to vary the potential difference (i.e. voltage) between the outer
14 pair or pairs of drive electrodes (i.e. in use).

15
16 It may be that the at least one electronic component is configured to provide a first
17 potential difference between the inner pair or pairs of drive electrodes and a second
18 potential difference between the outer pair or pair of drive electrodes. It may be that
19 the at least one electronic component is configured to provide said first and second
20 potential differences concurrently. The first and second potential differences are
21 typically similar (e.g. the same) in magnitude. The first and second potential
22 differences typically have opposing polarities.

23
24 The drive circuitry may comprise CMOS circuitry (e.g. CMOS electronics) integrated
25 with the substrate. CMOS electronic components (e.g. CMOS electronic components
26 forming part of CMOS circuitry, i.e. CMOS electronics) are typically formed (e.g. grown)
27 on the substrate by way of standard CMOS manufacturing methods. For example,
28 integrated CMOS electronic components may be deposited by way of one or more of
29 the following methods: physical vapour deposition, chemical vapour deposition,
30 electrochemical deposition, molecular beam epitaxy, atomic layer deposition, ion
31 implantation, photopatterning, reactive ion etching, plasma exposure.

32
33 It may be that the droplet ejector further comprises a protective layer covering the inner
34 and outer actuator arrangements and the nozzle-forming layer. The protective layer is
35 typically chemically inert, impermeable and/or fluid-repellent. The protective layer
36 should have a low Young's modulus (i.e. tensile elastic modulus). The protective layer
37 should have a Young's modulus which is substantially smaller than the Young's

1 modulus of the nozzle-forming layer (and in particular the nozzle-plate) and/or the
2 piezoelectric bodies. The protective layer typically has a Young's modulus less than
3 50GPa. The protective layer may be formed from one or more polymeric materials
4 such as polyimides or polytetrafluoroethylene (PTFE), diamond-like carbon (DLC),
5 negative or positive based photoresists, or epoxy-based photoresists (such as Su-8,
6 BCB), or any combination thereof. The protective layer may comprise two or more
7 layers of such different materials having different fluid wetting characteristics.

8
9 The droplet ejector is typically monolithic. The droplet ejector is typically integrated
10 (i.e. an integrated droplet ejector). The substrate, nozzle-forming layer, actuator
11 arrangements, fluid chamber, the at least one electronic component (e.g. of the drive
12 electronics) and the protective layer are typically integrated (i.e. with one another). The
13 droplet ejector is typically manufactured by integrally forming the substrate, nozzle-
14 forming layer, actuator arrangements, the at least one electronic component (e.g. of
15 the drive electronics) and the protective layer through one or more deposition
16 processes. The droplet ejector is not typically manufactured by bonding together one
17 or more individually-formed components (e.g. individually-formed substrates, nozzle-
18 forming layers, actuator arrangements, electronic components and/or protective
19 layers).

20
21 It may be that the mounting surface of the substrate comprises a fluid inlet aperture in
22 fluid communication with the fluid chamber.

23
24 The fluid chamber may be substantially elongate. The fluid chamber typically extends
25 from the mounting surface of the substrate to the nozzle surface. The fluid chamber
26 typically extends along a direction substantially perpendicular to the mounting surface
27 and/or the nozzle surface. The fluid chamber typically extends between the fluid inlet
28 aperture and the fluid chamber outlet.

29
30 The fluid chamber may be substantially circular in cross-section through the plane of
31 the substrate. The fluid chamber may be substantially polygonal in cross-section
32 through the plane of the substrate (for example, the fluid chamber may be substantially
33 square in cross-section). The fluid chamber may be many-sided in cross-section
34 through the plane of the substrate.

35

1 The fluid chamber may be substantially prismatic in shape. A longitudinal axis of the
2 substantially prismatic fluid chamber typically extends along the direction substantially
3 perpendicular to the mounting surface and/or the nozzle surface.

4
5 The fluid chamber may be substantially cylindrical in shape. A longitudinal axis of the
6 substantially cylindrical chamber typically extends along the direction substantially
7 perpendicular to the mounting surface and/or the nozzle surface.

8
9 The nozzle portion of the nozzle-forming layer is typically the portion of the nozzle-
10 forming layer which extends across the fluid chamber, thereby forming at least one wall
11 of the fluid chamber.

12
13 The nozzle portion of the nozzle-forming layer typically protrudes beyond the substrate
14 and is therefore bendable independently of the substrate.

15
16 It may be that the nozzle portion of the nozzle-forming layer is substantially annular.

17
18 It may be that the fluid chamber is substantially cylindrical and the nozzle portion of the
19 nozzle-forming layer is substantially annular.

20
21 The fluid chamber is typically bounded by one or more fluid chamber walls. At least
22 one of the one or more fluid chamber walls are typically formed by a portion of the
23 substrate. At least one of the one or more fluid chamber walls typically extend
24 substantially perpendicular (i.e. orthogonal) to the mounting surface and/or nozzle
25 surface of said substrate. Perpendicular (i.e. orthogonal) fluid chamber walls typically
26 permit closer packing of multiple adjacent fluid chambers (and thus droplet ejectors)
27 onto a single printhead, thereby increasing nozzle density. Perpendicular (i.e.
28 orthogonal) fluid chamber walls are typically formed by deep reactive-ion etching
29 (DRIE) methods, such as using the Bosch process.

30
31 It may be that the perimeter of the nozzle portion of the nozzle-forming layer is
32 substantially polygonal. It may be that the perimeter of the nozzle portion of the nozzle-
33 forming layer is many-sided. The nozzle portion of the nozzle-forming layer may be
34 lozenge-shaped. The nozzle portion of the nozzle-forming layer may be square-
35 shaped. Nevertheless, it may be that the nozzle portion of the nozzle-forming layer
36 (e.g. the polygonal, many-sided lozenge-shaped and/or square-shaped nozzle portion
37 of the nozzle-forming layer) may have rounded corners. The nozzle portion of the

1 nozzle-forming layer typically comprises an aperture. The aperture may be
2 substantially circular. The aperture may be substantially polygonal. The aperture may
3 be many-sided.

4
5 It may be that the fluid chamber is shaped in cross-section in the plane of the substrate
6 substantially similarly to the shape of the nozzle portion of the nozzle-forming layer.
7 For example, it may be that where the nozzle portion of the nozzle-forming layer is
8 square-shaped with rounded corners, the fluid chamber may be square-shaped with
9 rounded corners in cross-section.

10
11 It may be that the nozzle portion of the nozzle-forming layer (i.e. the portion of the
12 nozzle-forming layer which extends across the fluid chamber, thereby forming at least
13 one wall of the fluid chamber) is shaped substantially similarly to the shape of the fluid
14 chamber in cross-section in the plane of the substrate. For example, where the fluid
15 chamber is substantially cylindrical (i.e. substantially circular in cross section), the
16 perimeter of the nozzle portion of the nozzle-forming layer is substantially circular.

17
18 The printhead may be an inkjet printhead. The droplet ejector may be a droplet ejector
19 for (e.g. configured for use in) an inkjet printhead. The droplet ejector may be an inkjet
20 droplet ejector.

21
22 The printhead may be configured to print fluids (i.e. liquids), such as functional fluids,
23 for use in the manufacture of printed electronics.

24
25 The printhead may be configured to print biological fluids. Biological fluids typically
26 comprise biological macromolecules, e.g. polynucleotides, such as DNA or RNA,
27 microorganisms, and/or enzymes. The printhead may be configured to print other
28 fluids used in biological or biotechnological applications, such as diluents or reagents.

29
30 The printhead may be a voxel printhead (i.e. a printhead configured for use in 3D
31 printing, e.g. additive printing).

32
33 A second aspect of the invention provides a printhead comprising a plurality of droplet
34 ejectors according to the first aspect of the invention. It may be that (e.g. some or each
35 of) the plurality of droplet ejectors share a common substrate. For example, it may be
36 that the plurality of droplet ejectors are integrated on said common substrate.

1 The printhead may be an inkjet printhead. Each of the plurality of droplet ejectors may
2 be an inkjet droplet ejector.

3

4 The printhead may be configured to print functional fluids, such as for use in the
5 manufacture of printed electronics.

6

7 The printhead may be configured to print biological fluids. Biological fluids typically
8 comprise biological macromolecules, e.g. polynucleotides, such as DNA or RNA,
9 microorganisms, and/or enzymes. The printhead may be configured to print other
10 fluids used in biological or biotechnological applications, such as diluents or reagents.

11

12 The printhead may be a voxel printhead (i.e. a printhead configured for use in 3D
13 printing, e.g. additive printing).

14

15 A third aspect of the invention provides a printer comprising one or more printheads
16 according the second aspect of the invention.

17

18 A fourth aspect of the invention provides a method of actuating a droplet ejector
19 according to the first aspect of the invention. The method typically comprises actuating
20 the inner actuator arrangement and/or actuating the outer actuator arrangement to
21 thereby cause displacement of at least a portion of the nozzle portion of the nozzle-
22 forming layer and consequently ejection of fluid from the fluid chamber through the fluid
23 chamber outlet.

24

25 It may be that the droplet ejector comprises an inner actuator arrangement and an outer
26 actuator arrangement (i.e. the method is a method of actuating a droplet ejector
27 comprising: a substrate having a mounting surface and an opposite nozzle surface; a
28 nozzle-forming layer formed on at least a portion of the nozzle surface of the substrate;
29 a fluid chamber defined at least in part by the substrate and at least in part by the
30 nozzle-forming layer, the fluid chamber having a fluid chamber outlet defined at least
31 in part by a nozzle portion of the said nozzle-forming layer; an inner actuator
32 arrangement formed on at least a portion of the nozzle portion of the nozzle-forming
33 layer; and an outer actuator arrangement formed on at least a portion of the nozzle
34 portion of the nozzle-forming layer at least partially surrounding the inner actuator
35 arrangement).

36

1 It may be that the method comprises actuating both the inner actuator arrangement
2 and the outer actuator arrangement. Actuation of both the inner actuator arrangement
3 and the outer actuator arrangement typically causes deflection of at least a portion of
4 the nozzle portion of the nozzle-forming layer and consequently ejection of fluid from
5 the fluid chamber through the fluid chamber outlet (i.e. when fluid is stored in the fluid
6 chamber). The method therefore typically comprises providing fluid (i.e. liquid) in the
7 fluid chamber.

8

9 The steps of actuating the inner actuator arrangement and actuating the outer actuator
10 arrangement typically take place concurrently (i.e. at the same time).

11

12 The drive circuitry typically actuates both the inner actuator arrangement and the outer
13 actuator arrangement.

14

15 In embodiments in which the inner actuator arrangement comprises one or more inner
16 piezoelectric actuators, it may be that the method comprises applying a first potential
17 difference (i.e. voltage) between the inner pair or pairs of drive electrodes to cause
18 deflection of the inner piezoelectric body or bodies. In embodiments in which the outer
19 actuator arrangement comprises one or more outer piezoelectric actuators, it may be
20 that the method comprises applying a second potential difference (i.e. voltage)
21 between the outer pair or pairs of drive electrodes to cause deflection of the outer
22 piezoelectric body or bodies. It may be that method comprises applying the first and
23 second potential differences concurrently (i.e. at the same time). The drive circuitry
24 typically applies the first and second potential differences.

25

26 It may be that the first and second potential differences have similar (e.g. the same)
27 magnitudes. It may be that the first and second potential differences have opposing
28 polarities. Application of first and second potential differences having opposing
29 polarities typically results in deflection of the inner and outer piezoelectric bodies in
30 opposing directions.

31

32 It may be that the method comprises: first, actuating the inner actuator arrangement
33 and the outer actuator arrangement (e.g. concurrently) to cause deflection of at least a
34 portion of the nozzle portion of the nozzle-forming layer in a first direction; and, second,
35 actuating the inner actuator arrangement and the outer actuator arrangement (e.g.
36 concurrently) to cause deflection of at least a portion of the nozzle portion of the nozzle-
37 forming layer in a second direction opposite said first direction. Deflection of the

1 nozzle-forming layer in the first direction typically causes fluid to be drawn into the fluid
2 chamber, while deflection of the nozzle-forming layer in the second direction typically
3 causes ejection of fluid from the fluid chamber through the fluid chamber outlet.
4 Deflection of the nozzle-forming layer in the first direction before deflection in the
5 second direction also typically permits a greater ejection force to be exerted on the fluid
6 by displacement of the nozzle-portion through a greater distance on ejection.

7
8 Optional or preferred features of any one aspect of the invention may be optional or
9 preferred features of any other aspect of the invention.

10 Description of the Drawings

11
12
13 An example embodiment of the present invention will now be illustrated with reference
14 to the following Figures in which:

15
16 Figure 1 is a view of a monolithic fluid droplet ejector device including integrated
17 fluidics, electronic circuitry, nozzles and actuators according to a first embodiment;

18
19 Figure 2 is a cross-sectional view of the monolithic droplet ejector device along the line
20 F2 shown in Figure 1;

21
22 Figure 3 is a plan view of a nozzle showing features of the monolithic droplet ejector
23 shown in Figure 1 with a protective coating removed;

24
25 Figures 4(a) and 4(b) show a schematic of drive pulse implementations for the droplet
26 ejector device of Figure 1;

27
28 Figure 5 is a schematic of the manufacturing process flow for manufacturing the droplet
29 ejector device of Figure 1;

30
31 Figure 6 is a cross-sectional view showing an alternative implementation of the
32 electrode structure according to a second example embodiment of the invention;

33
34 Figure 7 is a schematic showing an alternative drive pulse implementation for the
35 droplet ejector device of Figure 6;

36

1 Figure 8 is a schematic showing a cross section through an alternative implementation
2 of the nozzle structure according to a third example embodiment of the invention;

4 Figure 9 is a cross-sectional view showing an alternative implementation of bond pad
5 structures according to a fourth example embodiment of the invention;

7 Figure 10 is a cross-sectional view through the nozzle structure on actuation of any of
8 the droplet ejector devices of Figure 1, Figure 6, Figure 8 or Figure 9;

10 Figure 11 provides both a cross-sectional view and a plan view of showing an
11 alternative monolithic droplet ejector having only an inner actuator arrangement
12 according to a fifth example embodiment of the invention;

14 Figure 12 is a cross-sectional view through the nozzle structure on actuation of the
15 droplet ejector device of Figure 11;

17 Figure 13 provides both a cross-sectional view and a plan view of showing an
18 alternative monolithic droplet ejector having only an outer actuator arrangement
19 according to a sixth example embodiment of the invention;

21 Figure 14 is a cross-sectional view through the nozzle structure on actuation of the
22 droplet ejector device of Figure 13;

24 Figure 15 is a plot of showing the volume swept by a droplet ejector device diaphragm
25 as a function of the location of the actuator arrangement;

27 Figure 16 shows in 3D the shape assumed by a diaphragm of a droplet ejector device
28 according to Figures 1, 6, 8, 9, 11 and 13 on actuation;

30 Figure 17 is a plot showing the deflection of the droplet ejector diaphragm for four
31 different actuation implementations; and

33 Figure 18 is a plot showing the deflection of the droplet ejector diaphragm for two
34 different actuator configurations as a function of location of the actuator arrangements
35 on the diaphragm.

36
37 Detailed Description of an Example Embodiment

1

2 *First Example Embodiment*

3

4 The first example embodiment is described with reference to Figures 1 to 5 and Figures
5 10 and 11.

6

7 Figure 1 shows a monolithic fluid droplet ejector device 1 including integrated fluidics,
8 electronic circuitry, nozzles and actuators according to the first example embodiment
9 of the invention. Figure 2 is a cross sectional view of the monolithic droplet ejector
10 device 1 along the line F2 shown in Figure 1.

11

12 As shown in Figure 1 and Figure 2, the fluid droplet ejector device is a monolithic chip
13 that includes a substrate 100, fluid inlet channel 101, electronic circuitry 200,
14 interconnect layer 300 comprising wiring, inner piezoelectric actuator 400, outer
15 piezoelectric actuator 450, nozzle plate 500, protective front surface 600, nozzle 601
16 and bond pad 700. Figure 1 shows a bond pad region 102 and a nozzle region 103.

17

18 The substrate 100 is typically between 20 and 1000 micrometres in thickness. The
19 interconnect layer 300, inner piezoelectric actuator 400, outer piezoelectric actuator
20 450, nozzle plate 500 and protective front surface 600 are typically between 0.5 and 5
21 micrometres in thickness. The nozzle 601 is typically between 3 and 50 micrometres
22 in diameter. The fluid inlet channel 103 has a characteristic dimension of between 50
23 and 800 micrometres.

24

25 The monolithic chip shown in Figure 1 comprises 4 rows of nozzles. Each row is offset
26 relative to adjacent rows in an alternating pattern. Any number of nozzle rows in
27 different configurations are possible. The arrangement of the nozzles on the chip is
28 configured to achieve a target print density (i.e. number of dots per inch (dpi)), a target
29 firing frequency and/or a target print speed. A range of different nozzle configurations
30 are possible which satisfy the particular printing requirements. Different printhead
31 nozzle configurations are effected by arranging individual nozzle and nozzle specific
32 drive electronics 201 and 202.

33

34 The substrate 100 is formed from a silicon wafer and comprises a supporting body 102,
35 fluid inlet channels 101 and electronic circuitry 200.

36

1 The fluid inlet channels 101 are formed through the thickness of the substrate 100 with
2 an opening at one surface at a fluid inlet 103 and are terminated at the other end by
3 the nozzle plate 500 and nozzles 601. The walls of the fluid inlet channels 101 have a
4 similar cross section through the substrate 100 and interconnect layer 300. The fluid
5 inlet channels 101 are substantially cylindrical (i.e. substantially circular in cross
6 section in the plane of the substrate). The corners of the fluid inlet channels 101, at
7 the interface with the nozzle plate and at the fluid inlet interface, are rounded to
8 minimize stress concentrations.

9
10 The electronic circuitry 200 is formed on the opposite surface of the substrate 100 to
11 the surface that includes the fluid inlets 103. The electronic circuitry 200 can include
12 digital and/or analog circuitry. Portions of the electronic circuitry, 201 and 202, are
13 connected directly to the inner and outer piezoelectric actuators 400 and 450 by way
14 of wiring 301 and 302 through the interconnect layer 300 and are located close to the
15 actuators 400 and 450 to optimize the application of a drive wave form. The electrode
16 actuator wiring interconnects 301 and 302 may be a continuous single construction or
17 they may be constructed from multiple layers of wiring. The drive electronics may be
18 configured to apply a set voltage or shaped voltage to the piezoelectric actuators for a
19 set period of time.

20
21 Portions of the electronic circuitry 203 are associated with the overall operation of the
22 entire monolithic droplet ejector device and can be located separate to the actuator
23 drive circuitry 201 and 202. The circuitry 203 associated with the general operation of
24 the chip can perform a range of functionalities including data routing, authentication,
25 chip monitoring (e.g. chip temperature monitoring), lifecycle management, yield
26 information processing and/or dead nozzle monitoring. The circuitry 203 is connected
27 to the bond pads 700 and the specific electrode drive circuitry 201 and 202 through the
28 interconnect layer 300. The chip drive electronics 203 may include analog and/or digital
29 circuits configured to perform different functions such as data caching, data routing,
30 bus management, general logic, synchronization, security, authentication, power
31 routing and/or input/output. The chip drive electronics 203 may comprise circuitry
32 components such as timing circuitry, interface circuitry, sensors and/or clocks.

33
34 There may be a number of general drive electronics areas located in different sections
35 of the chip - for example between nozzle rows or around the periphery of the chip.

36
37 The electronic drive circuitry includes 200 CMOS drive circuitry.

1
2 The interconnect layer 300 is formed directly on top of the electronics circuitry 200 and
3 the substrate 100 and comprises electrical insulator and wiring. Wiring in the
4 interconnect layer 300 connects chip electronic circuitry 203 to both the bond pads 700
5 and to the actuator electrode drive circuitry 201 and 202. The interconnect layer 300
6 includes power and data routing wiring which is routed between nozzles, around the
7 periphery of the chip and/or over drive electronics. The interconnect layer 300 typically
8 comprises multiple layers having different wiring paths.

9
10 A nozzle plate 500 is formed on top of the interconnect layer 300. The nozzle plate
11 500 is formed from either a single material or a laminate of multiple materials. The
12 nozzle plate 500 is continuous across the front surface of the chip with electrical
13 openings for wiring between the interconnect layer 300 below and actuator electrodes
14 401 above.

15
16 The nozzle plate 500 is formed from one or more materials which must be
17 manufacturable with the CMOS electronic drive circuitry 200 in terms of deposition
18 temperatures, compositions, and chemical processing steps. The nozzle plate
19 materials must also be chemically stable and impervious to the jetted fluids. The nozzle
20 plate materials must also be compatible with the functioning of the piezoelectric
21 actuator. For example, the Young's modulus of suitable materials lies in the range of
22 70 GPa to 300 GPa. However, variations in Young's modulus can be accommodated
23 by changing the thickness of the nozzle plate 500. Example nozzle plate materials
24 include one or more of (e.g. including combinations and/or laminates of) silicon dioxide
25 (SiO_2), silicon nitride (Si_3N_4), silicon carbide (SiC) and silicon oxynitride (SiO_xN_y).

26
27 Each outer piezoelectric actuator 450 comprises a laminate of a first electrode 451, a
28 piezoelectric layer 452 and a second electrode 453. The first electrode 451 is attached
29 to the nozzle plate 500. The piezoelectric layer 452 is attached to the first electrode
30 451. The second electrode 403 is attached to the piezoelectric layer surface opposite
31 the first electrode attachment surface. The first electrode 451 is electrically connected
32 to a wiring connection 301 in the interconnect layer 300. The second electrode 453 is
33 electrically connected to a wiring connection 302 in the interconnect layer 300. The first
34 electrode 451 and second electrode 453 are electrically isolated from each other.

35
36 Each inner piezoelectric actuator 400 comprises a laminate of a first electrode 401, a
37 piezoelectric layer 402 and a second electrode 403. The first electrode 401 is attached

1 to the nozzle plate 500. The piezoelectric layer 402 is attached to the first electrode
2 401. The second electrode 403 is attached to the piezoelectric layer surface opposite
3 the first electrode attachment surface. The first electrode 401 is electrically connected
4 to the second electrode 453 of the outer piezoelectric actuator. The second electrode
5 403 is electrically connected to the first electrode 451 of the outer piezoelectric
6 actuator. The first electrode 401 and second electrode 403 of the inner piezoelectric
7 actuator are electrically isolated from each other.

8
9 The electrode materials are electrically conductive and are typically formed from metals
10 or intermetallic compounds such as titanium (Ti), aluminium (Al), titanium-aluminide
11 (TiAl), tungsten (W) or platinum (Pt), or alloys thereof. These materials are
12 manufacturable (in terms of deposition temperature and chemical process
13 compatibility) with CMOS drive circuitry and the piezoelectric layer.

14
15 The piezoelectric layers 402 and 452 are formed from materials chosen for
16 compatibility with the manufacture of CMOS and interconnect circuitry. CMOS drive
17 circuitry can typically survive a temperature of up to about 450°C. However, high yield
18 manufacturing requires a much lower peak manufacturing temperature, typically
19 300°C. Deposition methods that subject the CMOS drive electronics to temperatures
20 over a duration can degrade performance, typically affecting dopant mobility and the
21 degradation of wiring within the interconnect layer. The temperature limit restricts
22 deposition methods for the piezoelectric layers. Suitable piezoelectric materials
23 include aluminium nitride (AlN), aluminium nitride compounds (in particular scandium
24 aluminium nitride (ScAlN)) and zinc oxide (ZnO), which are compatible with CMOS
25 electronics. The composition of the piezoelectric material is chosen to optimise the
26 piezoelectric properties. For example, the concentrations of any additional elements
27 in aluminium nitride compounds (such as the concentration of scandium in scandium
28 aluminium nitride) are typically chosen to optimise the magnitude of the d_{31}
29 piezoelectric constant. The higher the concentration of scandium in scandium
30 aluminium nitride, the typically larger the value of d_{31} . The mass percentage of
31 scandium in scandium aluminium nitride may be as high as 50%.

32
33 The piezoelectric actuator material is not continuous over the surface of the nozzle
34 plate 500. The piezoelectric material is located primarily over the nozzle plate and
35 includes a number of openings including electrode openings 404 and a region around
36 the nozzle 405.

1 The protective front surface 600 is formed on the outer surface of the droplet ejector
2 device 100 and covers the piezoelectric layers 402 and 452, the electrodes 401, 403,
3 451 and 453 and the nozzle plate 500. The protective front surface has openings for
4 the nozzles 601 and for the bond pads 700. The protective front surface material is
5 chemically inert and impermeable. The protective front surface material may also be
6 repellent to the fluid to be ejected. The mechanical properties of the protective front
7 surface material are chosen carefully to minimize the effect on the forcing action of the
8 piezoelectric actuators 400 and 450 and nozzle plate 500. The protective front surface
9 material is chosen to be manufacturable with a CMOS compatible process flow, for
10 example in terms of processing temperature and chemical process compatibility. The
11 protective front surface 600 prevents contact of fluid with any of the electrodes or the
12 piezoelectric layers. Suitable protective front surface materials include polyimides,
13 polytetrafluoroethylene (PTFE), diamond-like carbon (DLC) or related materials.

14

15 Figure 3 is a plan view of a nozzle showing features of the monolithic droplet ejector
16 structure 1 with the protective coating 600 removed according to the first embodiment.
17 The dashed line shows the underlying position of the fluid inlet 103 in relation to the
18 piezoelectric inner actuator 400 and the outer piezoelectric actuator 450.

19

20 In use, the fluid droplet ejector device 1 is mounted on a substrate that can supply fluid
21 to the fluid inlet 103. Fluid pressure is typically slightly negative at the fluid inlet 103
22 and the fluid inlet channels 101 typically "prime" or fill with fluid by surface tension
23 driven capillary action. The nozzles 601 prime up to the outer surface of the protective
24 front surface 600 due to capillary action once the fluid inlets 103 are primed. The fluid
25 does not move onto the outer surface of the protective surface 600 past the nozzles
26 601 due to the combination of negative fluid pressure and the geometry of the nozzle
27 601.

28

29 The actuator drive circuitry 201 and 202 controls the application of a voltage pulse to
30 the drive electrodes 401, 403, 451 and 453, according to a timing signal from the overall
31 drive circuitry 203. The application of electrode voltage across the piezoelectric
32 material layers 402 and 452 creates two electric fields. The electric fields cause
33 deformation of the piezoelectric material layers 402 and 452. The deformation can
34 either be a tensile or compressive strain depending on the orientation of the electric
35 field with respect to the local direction of polarization in the material. The induced strain
36 caused by the expansion or contraction of the piezoelectric materials 402 and 452
37 typically induces a strain gradient through the thickness of the nozzle plate 500,

1 piezoelectric actuators 400 and 450 and the protective front layer 600, causing a
2 movement or displacement of the nozzle plate relative to a neutral position.

3
4 The piezoelectric properties of the piezoelectric materials can be characterized in part
5 by the transverse piezoelectric constant d_{31} . d_{31} is the particular component of the
6 piezoelectric coefficient tensor which relates the electric field applied across the
7 piezoelectric material in a first direction to the strain induced in the piezoelectric
8 material along a second direction perpendicular to said first direction. The piezoelectric
9 actuators 400 and 450 shown are configured such that the applied electric fields induce
10 strains in the material layers in directions perpendicular to the directions in which the
11 fields are applied and are therefore characterized by the d_{31} constant.

12
13 Due to the uniform thickness and composition of both piezoelectric material layers 402
14 and 452, and due to the electrical cross-connections between electrodes 403 and 451
15 and electrodes 401 and 453, the application of a constant voltage or a voltage pulse
16 results in a first potential difference being applied across the inner actuator layer and
17 a second potential difference being applied across the outer actuator layer, wherein
18 the first and second potential differences are equal in magnitude but opposite in
19 polarity. Expressed in a different way, an electric field E_1 is set up across the inner
20 actuator piezoelectric layer and an electric field E_2 is set up across the outer actuator
21 piezoelectric layer, wherein E_1 and E_2 are equal in magnitude but act in opposite
22 directions. Because E_1 and E_2 act in opposite directions, the inner and outer actuator
23 layers deform in opposite senses. Dependent on the polarity of E_1 and E_2 ,
24 displacement X of the nozzle plate 500 is either positive or negative relative to a neutral
25 position (i.e. when there are no applied electric fields). A positive displacement of the
26 nozzle plate is shown in the upper portion of Figure 4(a) whereas a negative
27 displacement of the nozzle plate is shown in the lower portion of the figure.

28
29 The application of pulsed electric fields can cause oscillations of the nozzle plate 500.
30 Oscillation of the nozzle plate typically induces a pressure in the fluid inlet 103 under
31 the nozzle plate 500 which causes droplet ejection out of the nozzle 601. The frequency
32 and amplitude of the nozzle plate oscillation is primarily a function of the mass and
33 stiffness characteristics of the nozzle plate 500, piezoelectric actuators 400 and 450,
34 the protective layer 600, the fluid properties (for example, the fluid density, fluid
35 viscosity (either Newtonian or non-Newtonian) and surface tension), nozzle and fluid
36 inlet geometries and the configuration of both drive pulses.

37

1 Figures 4(a) and 4(b) show two drive pulse implementations. Voltage pulses across
2 the inner actuator electrodes 401 and 403 are shown in the diagram. It will be
3 understood that voltage pulses equal in magnitude but opposite in polarity are
4 simultaneously applied across outer actuator electrodes 451 and 453.

5
6 In a first implementation, the application of a steady state or DC electric field across
7 the electrode pairs causes a distortion of the piezoelectric layers 402 and 452 and a
8 steady state deflection of the nozzle plate away from the fluid inlet as shown in the
9 upper portion of Figure 4 (a). The fluid pressure under the nozzle plate is the same as
10 the fluid inlet supply pressure. Strain energy is stored in the nozzle plate 500, the
11 piezoelectric actuators 400 and 450 and the protective layer 600.

12
13 The electric fields are then removed and a reverse electric field pulse is applied as
14 shown in the lower portion of Figure 4 (a). This causes both a release of the stored
15 strain energy and further distortion of the piezoelectric materials in the opposite
16 direction. The nozzle plate moves towards the fluid inlet, which causes a positive
17 pressure in the fluid inlet and nozzle region and droplet ejection out of the nozzle 601.
18 The reverse electric field pulse may come immediately after the removal of the DC field
19 or at a slightly delayed duration.

20
21 The final removal of the electric fields across the piezoelectric materials causes the
22 nozzle plate 500 to return to a neutral position with no induced strain.

23
24 The application of electric fields of opposing polarity across the inner and outer
25 actuators causes the nozzle plate to deform into the shape shown in Figure 10. The
26 nozzle plate in the region of the inner actuator curves in an opposite sense relative to
27 the curvature of the nozzle plate in the region of the outer actuator, resulting in a
28 sigmoidal cross-section. This particular shape significantly increases the maximum
29 displacement of the nozzle portion of the nozzle plate from the neutral position when
30 compared to the displacement achievable when a nozzle plate is provided with only
31 one actuator causing curvature in only one sense. By increasing the maximum
32 displacement of the nozzle plate away from the neutral position, a much greater
33 ejection force can be exerted when the applied field is removed or reversed in polarity.
34 This enables the use of piezoelectric materials having low d_{31} constants, which are
35 normally considered unsuitable for use in inkjet printers due to the low forces they are
36 capable of generating. These low- d_{31} materials are typically processable at lower
37 temperatures, enabling closer integration of the droplet ejector with CMOS

1 components. The larger ejection forces achievable also permit the overall ejector size
2 to be reduced so that increased printhead nozzle densities are possible.

3
4 In a second implementation, the DC electric field configuration described in Figure 4(a)
5 with a pulse field configuration as shown in Figure 4(b). This has the advantage of
6 minimizing any applied strain effects over longer durations. An additional advantage
7 of the dual pulsed approach is enabled by the timing of the field pulse switching
8 application. The application of the first pulse will induce an oscillation with an initial
9 nozzle plate movement away from the fluid inlet as shown in the upper portion of Figure
10 4(b). This oscillation will introduce a negative fluid pressure under the nozzle plate
11 which introduces a net fluid flow towards the nozzle which can additionally augment
12 the fluid ejection flows through the nozzle.

13
14 Figure 5 is a schematic showing the manufacturing process flow for the droplet ejector
15 device. The first manufacturing step, as shown in Figure 5(a), is to create drive circuitry
16 and the interconnect layer 300, for example CMOS drive circuitry and interconnects,
17 on a surface of a silicon wafer substrate. CMOS drive circuitry is formed by standard
18 processes - for example ion implantation on p-type or n-type substrates followed by the
19 creation of a wiring interconnect layer by standard CMOS fabrication processes (e.g.
20 ion implantation, chemical vapour deposition (CVD), physical vapour deposition (PVD),
21 etching, chemical-mechanical planarization (CMP) and/or electroplating).

22
23 Subsequent manufacturing steps are implemented to define features and structures of
24 the monolithic droplet ejector device. Subsequent steps are chosen not to damage
25 structures formed in previous steps. A key manufacturing parameter is the peak
26 processing temperature. Problems associated with processing CMOS at high
27 temperatures include the degradation of dopant mobility and interconnect wiring
28 schemes. CMOS electronics are known to survive temperatures of 450°C. However,
29 a much lower temperature (i.e. below 300°C) is desirable for high yield.

30
31 The nozzle plate 500, the piezoelectric actuators 400 and 450, the protective layer 600
32 and the bond pads 700 are formed on top of the interconnect layer as shown in Figure
33 5(b).

34
35 The nozzle plate 500 is deposited using a CVD or PVD process.

36

1 The formation of a CMOS compatible piezoelectric material 402 and 452 is of particular
2 interest as this is the key driving element of the actuator. Table 1 lists some common
3 piezoelectric materials and the manufacturing methods associated with them, along
4 with typical d_{31} values. It can be seen that materials with the highest d_{31} values are
5 incompatible with manufacture of monolithic CMOS structures. Materials that are
6 compatible with CMOS structures have low d_{31} values and hence a much lower forcing
7 capability.

8
9 As can be seen from the table, although lead zirconate titanate (PZT) can be deposited
10 by PVD (including sputtering) at low temperatures, it subsequently requires a post
11 process anneal at a temperature above the allowable temperature for CMOS. PZT can
12 also be deposited by sol gel methods, but this again requires a high temperature anneal
13 above the CMOS limit. PZT also has a very slow rate of deposition that is not viable
14 commercially. PZT additionally contains lead, which is undesirable environmentally.

15
16 ZnO, AlN and AlN compounds (such as ScAlN) materials can be deposited using low-
17 temperature PVD (e.g. sputtering) processes that do not require post processing such
18 as annealing. These materials also do not require poling. A poling step is required for
19 PZT, wherein the material is subjected to a very high electric field which orients all the
20 electric dipoles in the direction of the field.

21
22 ZnO, AlN and AlN compounds (e.g. ScAlN) materials are therefore commercially viable
23 materials for the fabrication of a monolithic droplet ejector device. However, the value
24 of d_{31} for these materials is significantly lower than that of PZT. The particular
25 configuration of the nozzle (i.e. the actuatable nozzle plate), which improves ejection
26 efficiency, and the use of two pairs of control electrodes, which improves actuation
27 efficiency, counter the lower d_{31} value associated with these materials.

28
29 Actuator electrode materials are deposited using a CMOS compatible process such as
30 PVD (including low-temperature sputtering). Typical electrode materials may include
31 titanium (Ti), platinum (Pt), aluminium (Al), tungsten (W), molybdenum (Mo) or alloys
32 thereof. The electrodes are defined by standard patterning and etch methods.

33
34 Protective materials can be deposited and patterned using a spin on and cure method
35 (suitable for polyimides or other polymeric materials). Some materials, such as PTFE,
36 may require more specific deposition and patterning approaches.

37

1 Bond pads are deposited using methods such as CVD or PVD (e.g. sputtering).

2
3 The fluid inlet channels are defined using high aspect ratio Deep Reactive Ion Etching
4 (DRIE) methodologies as shown in Figure 5(c). The fluid inlets are aligned to the
5 nozzle structures using a wafer front-back side alignment tool. The wafer may be
6 mounted on a handle wafer during the front-back alignment and etch steps.

7
8 The DRIE approach may also be used to singulate the die, however, other approaches
9 may be used such as a wafer saw.

10
11 *Second Example Embodiment*

12
13 Figure 6 is a cross sectional view showing an alternative implementation of the
14 electrode structure. In this embodiment the electrodes 403 and 453 are connected by
15 wiring, 302, to a ground line 204 rather than drive circuitry. The ground line 204 is
16 located within the interconnect layer 300 and is connected to the drive circuitry region
17 203 or directly to grounded bond pads 700.

18
19 *Third Example Embodiment*

20
21 Figure 7 is a schematic showing an alternative drive pulse implementation compatible
22 with this droplet ejector device. A voltage pulse, as shown in Figure 7, is applied to
23 only one electrode of each electrode pair, for example 401 and 453. This creates an
24 electric field through the piezoelectric actuators 400 and 450 that creates a downward
25 overall displacement of the nozzle plate 500. It is also possible to configure the device
26 with a drive pulse applied to electrodes 403 and 451 and a ground voltage applied to
27 electrode 401 and 453.

28
29 *Fourth Example Embodiment*

30
31 Figure 8 is a schematic showing a cross section of an alternative implementation of the
32 nozzle structure and shows the extension of the interconnect layer 304 attached to the
33 nozzle plate layer 500 in the vicinity of the fluid inlet 101. The interconnect layer
34 extension 304 may comprise solely dielectric material without any wiring. In another
35 variation, the device has no nozzle plate layer and only an interconnect layer attached
36 to the piezoelectric actuator.

37

1 *Fifth Example Embodiment*

2

3 Figure 9 is a cross-sectional view showing an alternative implantation of the bond pad
4 structures. The protective front surface has been removed in the vicinity of the bond
5 pads 701. This geometry improves accessibility of external wiring schemes and
6 reduces the overall height of wire bonding above the height of the chip.

7

8 *Sixth and Seventh Example Embodiments*

9

10 Figure 11 is a schematic showing a cross section and plan view of an alternative
11 implementation of the nozzle structure which includes only an inner piezoelectric
12 actuator 400 adjacent the fluid outlet 601. In this embodiment, the piezoelectric
13 material only extends between the electrodes 401 and 402 and does not extend
14 beyond the electrodes over the remainder of the nozzle plate layer 500 (i.e. it does not
15 extend into the region 450 where an outer piezoelectric actuator might be expected to
16 be located).

17

18 The application of an electric field across the inner actuator causes the nozzle plate to
19 deform into the shape shown in Figure 12. Actuation of the inner actuator causes the
20 inner portion of the nozzle plate to curve in a first sense. The outer portion of the nozzle
21 plate in response curves in an opposite sense, resulting in a sigmoidal cross-section.
22 This particular shape significantly increases the maximum displacement of the nozzle
23 portion of the nozzle plate from the neutral position when compared to the
24 displacement achievable when a nozzle plate is provided with only one actuator
25 extending over the majority of the nozzle plate, which typically causes curvature in only
26 one sense.

27

28 In addition, Figure 13 is a schematic showing a cross section and plan view of an
29 alternative implementation of the nozzle structure which includes only an outer
30 piezoelectric actuator 450 adjacent the fluid outlet 601. In this embodiment, the
31 piezoelectric material only extends between the electrodes 401 and 402 and does not
32 extend beyond the electrodes over the remainder of the nozzle plate layer 500 (i.e. it
33 does not extend into the region 400 where an inner piezoelectric actuator might be
34 expected to be located).

35

36 The application of an electric field across the outer actuator causes the nozzle plate to
37 deform into the shape shown in Figure 12. Actuation of the outer actuator causes the

1 outer portion of the nozzle plate to curve in a first sense. The inner portion of the nozzle
2 plate in response curves in an opposite sense, resulting in a sigmoidal cross-section.
3 This particular shape significantly increases the maximum displacement of the nozzle
4 portion of the nozzle plate from the neutral position when compared to the
5 displacement achievable when a nozzle plate is provided with only one actuator
6 extending over the majority of the nozzle plate, which typically causes curvature in only
7 one sense.

8
9 Figure 15 shows the volume swept by the nozzle plate on actuation as a function of the
10 radial location of a single annular actuator positioned symmetrically about the fluid
11 outlet. In this case the layer of piezoelectric material extends across the entire nozzle
12 plate and the location of the actuator is defined by the location of first and second
13 actuator electrodes. The nozzle plate has an outer radius of 125 microns. It can be
14 seen from this Figure that the maximum swept volume (and therefore fluid ejection) is
15 achievable for an actuator located close to the outer periphery (at a location 105
16 microns from the centre) of the nozzle plate. Figure 16 shows the 3D shape taken up
17 by the nozzle plate on actuation of a single annular actuator located closer to the outer
18 periphery. The inner portion of the nozzle plate can be seen to curve in an opposite
19 sense from the outer portion of the nozzle plate.

20
21 Figure 17 shows how the deflection of the nozzle plate from a neutral position (i.e.
22 before actuation of any actuators) varies as a function of radial location across the
23 nozzle plate in embodiments comprising both inner and outer piezoelectric actuators.
24 The Figure shows data sets for: "Reversed Polarity" (both inner and outer annular
25 actuators are provided, each being actuated concurrently by electric fields having
26 opposed polarities); "Similar Polarity" (both inner and outer annular actuators are
27 provided, each being actuated concurrently by electric fields having the same polarity);
28 "Inner only" (both inner and outer annular actuators are provided, but only the inner
29 actuator is actuated); and "Outer only" (both inner and outer annular actuators are
30 provided, but only the outer actuator is actuated). In such embodiments, maximum
31 deflection is achieved when electric fields having opposing polarities are applied to the
32 inner and outer actuators.

33
34 Figure 18 also shows how the deflection of the nozzle plate from the neutral position
35 varies as a function of radial location across the nozzle plate for embodiments
36 comprising only a single piezoelectric actuator in which the piezoelectric material does
37 not extend beyond said piezoelectric actuator. In such embodiments, maximum

1 deflection is achieved when an inner actuator is provided. The lack of piezoelectric
2 material in the region *not* containing an actuator leads to increased flexibility and
3 therefore potentially greater deflections can be achieved by ejectors incorporating a
4 single annular piezoelectric actuator (whether inner or outer) compared to ejectors
5 incorporating both inner and outer piezoelectric actuators.

6
7 Further variations and modifications may be made within the scope of the invention
8 herein disclosed.

9
10 The device may be formed on a silicon wafer substrate. Alternatively, the substrate
11 may comprise a silicon-on-insulator wafer or III-V semiconductor wafer.

12
13 The fluid inlet channels may be substantially cylindrical and therefore have
14 substantially circular cross-sections in the plane of the substrate. Alternatively, the
15 fluid inlet channels may take a variety of other cross-sections including multiple-sided,
16 regular or irregular shapes. The shape of the fluid inlet channels is typically dependent
17 on other aspects of the monolithic chip design such as the layout of nozzles, the drive
18 electronics placement and the wiring routing in the interconnect layer 300.

19
20 The cross-sectional shapes may also be selected to minimize the width of the printhead
21 chip without introducing failure mechanisms. Failure mechanisms may be structural
22 (for example, too many fluid inlets may reduce the robustness of the chip) or they may
23 be operational (for example, interconnect wires may be insufficient to carry the
24 appropriate current). A reduced printhead width is desirable because it increases the
25 number of chips which can be manufactured on a single wafer.

26
27 Further variations and modifications may be made within the scope of the invention
28 herein disclosed.

29

1 Claims

2

- 3 1. A droplet ejector for a printhead, the droplet ejector comprising: a substrate
4 having a mounting surface and an opposite nozzle surface; a nozzle-
5 forming layer formed on at least a portion of the nozzle surface of the
6 substrate; a fluid chamber defined at least in part by the substrate and at
7 least in part by the nozzle-forming layer, the fluid chamber having a fluid
8 chamber outlet defined at least in part by a nozzle portion of the said nozzle-
9 forming layer, the said nozzle portion comprising an inner portion located
10 closer to the fluid chamber outlet and an outer portion located closer to a
11 periphery of the nozzle portion; and either or both of an inner actuator
12 arrangement formed on the inner portion of the nozzle portion of the nozzle-
13 forming layer and an outer actuator arrangement formed on the outer
14 portion of the nozzle portion of the nozzle-forming layer.
- 15 2. The droplet ejector according to claim 1, wherein the outer portion of the
16 nozzle portion of the nozzle-forming layer at least partially surrounds the
17 inner portion of the nozzle portion of the nozzle-forming layer.
- 18 3. The droplet ejector according to claim 1 or claim 2, wherein the inner
19 actuator arrangement at least partially surrounds the fluid chamber outlet.
- 20 4. The droplet ejector according to any one preceding claim, wherein both the
21 inner and/or outer actuator arrangements are substantially annular.
- 22 5. The droplet ejector according to any one preceding claim further comprising
23 at least one electronic component integrated with the substrate.
- 24 6. The droplet ejector according to any one preceding claim comprising an
25 inner actuator arrangement which comprises one or more inner
26 piezoelectric actuators, at least one of said one or more inner piezoelectric
27 actuators comprising an inner piezoelectric body provided between an inner
28 pair of drive electrodes.
- 29 7. The droplet ejector according to claim 6, wherein the inner actuator
30 arrangement consists of a single inner piezoelectric actuator which is
31 substantially annular.
- 32 8. The droplet ejector according to any one preceding claim comprising an
33 outer actuator arrangement which comprises one or more outer
34 piezoelectric actuators, at least one of said one or more outer piezoelectric
35 actuators comprising an outer piezoelectric body provided between an
36 outer pair of drive electrodes.

- 1 9. The droplet ejector according to claim 8, wherein the outer actuator
2 arrangement consists of a single outer piezoelectric actuator which is
3 substantially annular.
- 4 10. The droplet ejector according to claim 9 dependent on claim 7, wherein the
5 single outer piezoelectric actuator surrounds the single inner piezoelectric
6 actuator.
- 7 11. The droplet ejector according to any one of claims 8 to 10 dependent on
8 claim 6, wherein both the inner and outer pairs of drive electrodes are
9 electrically connected to a drive circuit configured to, when in use and
10 connected to a power supply, apply a first potential difference between the
11 inner pair of electrodes to cause deflection of the inner piezoelectric body
12 in a first direction and to apply a second potential difference between the
13 outer pair of electrodes to cause deflection of the outer piezoelectric body
14 in a second direction opposite said first direction.
- 15 12. The droplet ejector according to any one of claims 6 to 11, wherein the inner
16 piezoelectric body or bodies and/or the outer piezoelectric body or bodies
17 comprise one or more piezoelectric materials processable at a temperature
18 below 450°C.
- 19 13. The droplet ejector according to any one of claims 6 to 12, wherein the inner
20 piezoelectric body or bodies and/or the outer piezoelectric body or bodies
21 comprise one or more piezoelectric materials depositable at a temperature
22 below 450°C.
- 23 14. The droplet ejector according to claim 12 or claim 13, wherein the one or
24 more piezoelectric materials are PVD-deposited piezoelectric materials.
- 25 15. The droplet ejector according to any one of claims 12 to 14, wherein the one
26 or more piezoelectric materials comprise aluminium nitride and/or zinc
27 oxide.
- 28 16. The droplet ejector according to claim 15, wherein aluminium nitride further
29 comprises one or more of the following elements: scandium, yttrium,
30 titanium, magnesium, hafnium, zirconium, tin, chromium, boron.
- 31 17. The droplet ejector according to any one of claims 12 to 16, wherein the one
32 or more piezoelectric materials comprise ceramic material comprising
33 aluminium and nitrogen and optionally one or more elements selected from:
34 scandium, yttrium, titanium, magnesium, hafnium, zirconium, tin,
35 chromium, boron.
- 36 18. The droplet ejector according to any one of claims 12 to 17, wherein the one
37 or more piezoelectric materials are non-ferroelectric piezoelectric materials.

- 1 19. The droplet ejector according to any one of claims 6 to 18, wherein the inner
2 piezoelectric body or bodies and/or the outer piezoelectric body or bodies
3 have d_{31} piezoelectric constants having magnitudes less than 20 pC/N.
- 4 20. The droplet ejector according to any one preceding claim further comprising
5 at least one electronic component integrated with the substrate.
- 6 21. The droplet ejector according to any one preceding claim, wherein the
7 mounting surface of the substrate comprises a fluid inlet aperture in fluid
8 communication with the fluid chamber.
- 9 22. The droplet ejector according to any one preceding claim, wherein the fluid
10 chamber is substantially cylindrical and the nozzle portion of the nozzle-
11 forming layer is substantially annular.
- 12 23. The droplet ejector according to any one preceding claim further comprising
13 a protective layer covering the inner and outer actuator arrangements and
14 the nozzle-forming layer.
- 15 24. A printhead comprising a plurality of droplet ejectors according to any one
16 preceding claim.
- 17 25. The printhead according to claim 24, wherein the plurality of droplet ejectors
18 share a common substrate.
- 19 26. A printer comprising one or more printheads according to claim 24 or claim
20 25.
- 21 27. A method of actuating a droplet ejector according to any one of claims 1 to
22 20, the method comprising: actuating the inner actuator arrangement and/or
23 actuating the outer actuator arrangement to thereby cause displacement of
24 at least a portion of the nozzle portion of the nozzle-forming layer and
25 consequently ejection of fluid from the fluid chamber through the fluid
26 chamber outlet.
- 27 28. The method according to claim 27, wherein the droplet ejector comprises
28 both an inner actuator arrangement and an outer actuator arrangement, the
29 method comprising: actuating both the inner actuator arrangement and the
30 outer actuator arrangement to thereby cause displacement of at least a
31 portion of the nozzle portion of the nozzle-forming layer and consequently
32 ejection of fluid from the fluid chamber through the fluid chamber outlet.
- 33 29. The method according to claim 28, wherein the steps of actuating the inner
34 actuator arrangement and actuating the outer actuator arrangement take
35 place concurrently.
- 36 30. The method according to claim 28 or claim 29, dependent on claim 11,
37 wherein actuating the inner actuator arrangement comprises applying a first

- 1 potential difference between the inner pair of drive electrodes to cause
2 deflection of the inner piezoelectric body and wherein actuating the outer
3 actuator arrangement comprises applying a second potential difference
4 between the outer pair of drive electrodes to cause deflection of the outer
5 piezoelectric body.
- 6 31. The method according to claim 30, wherein the first and second potential
7 differences have opposing polarities such that the inner piezoelectric body
8 and the outer piezoelectric body deflect in opposing directions.
- 9 32. The method according to claim 30 or claim 31, wherein the first and second
10 potential differences are applied concurrently.
11
12