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(54) **Inkjet nozzle with magnetic actuator chamber**

Tintenstrahldüse mit magnetischer Antriebskammer

Buse de jet d'encre avec chambre-actuateur magnétique

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(73) Proprietor: **Silverbrook Research Pty. Limited**
Balmain, NSW 2041 (AU)

(72) Inventor: **Silverbrook, Kia**
Leichhardt
NSW 2040 (AU)

(74) Representative: **Moore, Barry et al**
Hanna, Moore & Curley
13 Lower Lad Lane
Dublin 2 (IE)

(56) References cited:
WO-A-97/12689

- **PATENT ABSTRACTS OF JAPAN** vol. 0143, no. 95 (M-1016), 27 August 1990 (1990-08-27) & JP 2 150353 A (NEC HOME ELECTRON LTD), 8 June 1990 (1990-06-08)

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Description**Field of Invention**

5 **[0001]** The present invention relates to the field of ink jet printing systems.

Background of the Art

10 **[0002]** Many different types of printing have been invented, a large number of which are presently in use. The known forms of print have a variety of methods for marking the print media with a relevant marking media. Commonly used forms of printing include offset printing, laser printing and copying devices, dot matrix type impact printers, thermal paper printers, film recorders, thermal wax printers, dye sublimation printers and ink jet printers both of the drop on demand and continuous flow type. Each type of printer has its own advantages and problems when considering cost, speed, quality, reliability, simplicity of construction and operation etc.

15 **[0003]** In recent years, the field of ink jet printing, wherein each individual pixel of ink is derived from one or more ink nozzles has become increasingly popular primarily due to its inexpensive and versatile nature.

[0004] Many different techniques of ink jet printing have been invented. For a survey of the field, reference is made to an article by J Moore, "Non-Impact Printing: Introduction and Historical Perspective", Output Hard Copy Devices, Editors R Dubeck and S Sherr, pages 207-220 (1988).

20 **[0005]** Ink jet printers themselves come in many different types. The utilisation of a continuous stream ink in ink jet printing appears to date back to at least 1929 wherein US Patent No. 1941001 by Hansell discloses a simple form of continuous stream electro-static ink jet printing.

[0006] US Patent 3596275 by Sweet also discloses a process of a continuous ink jet printing including the step wherein the ink jet stream is modulated by a high frequency electro-static field so as to cause drop separation. This technique is still utilized by several manufacturers including Elmjett and Scitex (see also US Patent No. 3373437 by Sweet et al)

25 **[0007]** Piezo-electric ink jet printers are also one form of commonly utilized ink jet printing device. Piezo-electric systems are disclosed by Kyser et. al. in US Patent No. 3946398 (1970) which utilises a diaphragm mode of operation, by Zolten in US Patent 3683212 (1970) which discloses a squeeze mode of operation of a piezo electric crystal, Stemme in US Patent No. 3747120 (1972) discloses a bend mode of piezo-electric operation, Howkins in US Patent No. 4459601 discloses a Piezo electric push mode actuation of the ink jet stream and Fischbeck in US 4584590 which discloses a sheer mode type of piezo-electric transducer element.

30 **[0008]** Recently, thermal ink jet printing has become an extremely popular form of ink jet printing. The ink jet printing techniques include those disclosed by Endo et al in GB 2007162 (1979) and Vaught et al in US Patent 4490728. Both the aforementioned references disclosed ink jet printing techniques rely upon the activation of an electrothermal actuator which results in the creation of a bubble in a constricted space, such as a nozzle, which thereby causes the ejection of ink from an aperture connected to the confined space onto a relevant print media. Printing devices utilising the electro-thermal actuator are manufactured by manufacturers such as Canon and Hewlett Packard.

35 **[0009]** WO97/12689 describes an inkjet nozzle comprising a deflectable membrane having a nozzle opening defined therein. The membrane is laminated to a magnetic transducer, which may be actuated by another transducer placed behind a piece of paper.

40 **[0010]** As can be seen from the foregoing, many different types of printing technologies are available. Ideally, a printing technology should have a number of desirable attributes. These include inexpensive construction and operation, high speed operation, safe and continuous long term operation etc. Each technology may have its own advantages and disadvantages in the areas of cost, speed, quality, reliability, power usage, simplicity of construction operation, durability and consumables.

45 **[0011]** Many ink jet printing mechanisms are known. Unfortunately, in mass production techniques, the production of ink jet heads is quite difficult. For example, often, the orifice or nozzle plate is constructed separately from the ink supply and ink ejection mechanism and bonded to the mechanism at a later stage (Hewlett-Packard Journal, Vol. 36 no 5, pp33-37 (1985)). These separate material processing steps required in handling such precision devices often adds a substantially expense in manufacturing.

[0012] Additionally, side shooting ink jet technologies (U.S. Patent No. 4,899,181) are often used but again, this limit the amount of mass production throughput given any particular capital investment.

50 **[0013]** Additionally, more esoteric techniques are also often utilized. These can include electroforming of nickel stage (Hewlett-Packard Journal, Vol. 36 no 5, pp33-37 (1985)), electro-discharge machining, laser ablation (U.S. Patent No. 5,208,604), micro-punching, etc.

[0014] The utilisation of the above techniques is likely to add substantial expense to the mass production of ink jet print heads and therefore add substantially to their final cost.

[0015] It would therefore be desirable if an efficient system for the mass production of ink jet print heads could be

developed.

Summary of the invention

[0016] It is an object of the present invention to provide for an ink jet printing mechanism having a series of ink ejection nozzles, with the nozzles including an internal selective actuator mechanism activated on a nozzle by nozzle basis by the placement of a field around said nozzles.

[0017] Accordingly the invention provides an arrangement according to claim 1. Advantageous embodiments are provided in the dependent claims.

Brief Description of the Drawings

[0018] Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Fig. 327 to Fig. 329 are schematic illustrations of the operation of an ink jet nozzle arrangement of an embodiment.

Fig. 330 illustrates a side perspective view, partly in section, of a single ink jet nozzle arrangement of an embodiment;

Fig. 331 provides a legend of the materials indicated in Fig. 332 to Fig. 347;

Fig. 332 to Fig. 347 illustrate sectional views of the manufacturing steps in one form of construction of an ink jet printhead nozzle;

Description of the Preferred and Other Embodiments

[0019] The preferred embodiments and other embodiments will be discussed under separate headings with the heading including an IJ number for ease of reference. The headings also include a type designator with T indicating thermal, S indicating shutter type and F indicating a field type.

Description of IJ45 F

[0020] In an embodiment, an ink jet print head is constructed from a series of nozzle arrangements where each nozzle arrangement includes a magnetic plate actuator which is actuated by a coil which is pulsed so as to move the magnetic plate and thereby cause the ejection of ink. The movement of the magnetic plate results in a leaf spring device being extended resiliently such that when the coil is deactivated, the magnetic plate returns to a rest position resulting in the ejection of a drop of ink from an aperture created within the plate.

[0021] Turning now to Fig. 327 to Fig. 329, there will now be explained the operation of this embodiment.

[0022] Turning to Fig. 327, there is illustrated an ink jet nozzle arrangement 4401 which includes a nozzle chamber 4402 which connects with an ink ejection nozzle 4403 such that, when in a quiescent position, an ink meniscus 4404 forms over the nozzle 4403. The nozzle 4403 is formed in a magnetic nozzle plate 4405 which can be constructed from a ferrous material. Attached to the nozzle plate 4405 is a series of leaf springs e.g. 4406, 4407 which bias the nozzle plate 4405 away from a base plate 4409. Between the nozzle plate 4405 and the base plate 4409, there is provided a conductive coil 4410 which is interconnected and controlled via a lower circuitry layer 4411 which can comprise a standard CMOS circuitry layer. The ink chamber 4402 is supplied with ink from a lower ink supply channel 4412 which is formed by etching through a wafer substrate 4413. The wafer substrate 4413 can comprise a semiconductor wafer substrate. The ink chamber 4402 is interconnected to the ink supply channel 4412 by means of a series of slots 4414 which can be etched through the CMOS layer 4411.

[0023] The area around the coil 4410 is hydrophobically treated so that, during operation, a small meniscus e.g. 4416, 4417 forms between the nozzle plate 4405 and base plate 4409.

[0024] When it is desired to eject a drop of ink, the coil 4410 is energised. This results in a movement of the plate 4405 as illustrated in Fig. 328. The general downward movement of the plate 4405 results in a substantial increase in pressure within nozzle chamber 4402. The increase in pressure results in a rapid growth in the meniscus 4404 as ink flows out of the nozzle chamber 4403. The movement of the plate 4405 also results in the springs 4406, 4407 undergoing a general resilient extension. The small width of the slot 4414 results in minimal outflows of ink into the nozzle chamber 4412.

[0025] Moments later, as illustrated in Fig. 329, the coil 4410 is deactivated resulting in a return of the plate 4405 towards its quiescent position as a result of the springs 4406, 4407 acting on the nozzle plate 4405. The return of the nozzle plate 4405 to its quiescent position results in a rapid decrease in pressure within the nozzle chamber 4402 which in turn results in a general back flow of ink around the ejection nozzle 4403. The forward momentum of the ink outside the nozzle plate 4403 and the back suction of the ink around the ejection nozzle 4403 results in a drop 4419 being

formed and breaking off so as to continue to the print media.

[0026] The surface tension characteristics across the nozzle 4403 result in a general inflow of ink from the ink supply channel 4412 until such time as the quiescent position of Fig. 327 is again reached. In this manner, a coil actuated magnetic ink jet print bead is formed for the adoption of ink drops on demand. Importantly, the area around the coil 4410 is hydrophobically treated so as to expel any ink from flowing into this area.

[0027] Turning now to Fig. 330, there is illustrated a side perspective view, partly in section of a single nozzle arrangement constructed in accordance with the principles as previously outlined with respect to Fig. 327 to Fig. 329. The arrangement 4401 includes a nozzle plate 4405 which is formed around an ink supply chamber 4402 and includes an ink ejection nozzle 4403. A series of leaf spring elements 4406-4408 are also provided which can be formed from the same material as the nozzle plate 4405. A base plate 4409 also is provided for encompassing the coil 4410. The wafer 4413 includes a series of slots 4414 for the wicking and flowing of ink into nozzle chamber 4402 with the nozzle chamber 4402 being interconnected via the slots with an ink supply channel 4412. The slots 4414 are of a thin elongated form so as to provide for fluidic resistance to a rapid outflow of fluid from the chamber 4402.

[0028] The coil 4410 is conductive interconnected at a predetermined portion (not shown) with a lower CMOS layer for the control and driving of the coil 4410 and movement of base plate 4405. Alternatively, the plate 4409 can be broken into two separate semi-circular plates and the coil 4410 can have separate ends connected through one of the semi circular plates through to a lower CMOS layer.

[0029] Obviously, an array of ink jet nozzle devices can be formed at a time on a single silicon wafer so as to form multiple printheads.

[0030] One form of detailed manufacturing process which can be used to fabricate monolithic ink jet print heads operating in accordance with the principles taught by the present embodiment can proceed utilizing the following steps:

1. Using a double sided polished wafer, complete a 0.5 micron, one poly, 2 metal CMOS process. Due to high current densities, both metal layers should be copper for resistance to electromigration. This step is shown in Fig. 332. For clarity, these diagrams may not be to scale, and may not represent a cross section though any single plane of the nozzle. Fig. 331 is a key to representations of various materials in these manufacturing diagrams, and those of other cross referenced ink jet configurations.

2. Etch the CMOS oxide layers down to silicon or aluminum using Mask 1. This mask defines the nozzle chamber inlet cross, the edges of the print heads chips, and the vias for the contacts from the second level metal electrodes to the two halves of the split fixed magnetic plate.

3. Plasma etch the silicon to a depth of 15 microns, using oxide from step 2 as a mask. This etch does not substantially etch the second level metal. This step is shown in Fig. 333.

4. Deposit a seed layer of cobalt nickel iron alloy. CoNiFe is chosen due to a high saturation flux density of 2 Tesla, and a low coercivity. [Osaka, Tetsuya et al, A soft magnetic CoNiFe film with high saturation magnetic flux density, Nature 392, 796-798 (1998)].

5. Spin on 4 microns of resist, expose with Mask 2, and develop. This mask defines the split fixed magnetic plate, for which the resist acts as an electroplating mold. This step is shown in Fig. 334.

6. Electroplate 3 microns of CoNiFe. This step is shown in Fig. 335.

7. Strip the resist and etch the exposed seed layer. This step is shown in Fig. 336.

8. Deposit 0.5 microns of silicon nitride, which insulates the solenoid from the fixed magnetic plate.

9. Etch the nitride layer using Mask 3. This mask defines the contact vias from each end of the solenoid coil to the two halves of the split fixed magnetic plate, as well as returning the nozzle chamber to a hydrophilic state. This step is shown in Fig. 337.

10. Deposit an adhesion layer plus a copper seed layer. Copper is used for its low resistivity (which results in higher efficiency) and its high electromigration resistance, which increases reliability at high current densities.

11. Spin on 13 microns of resist and expose using Mask 4, which defines the solenoid spiral coil, for which the resist acts as an electroplating mold. As the resist is thick and the aspect ratio is high, an X-ray proximity process, such as LIGA, can be used. This step is shown in Fig. 338.

12. Electroplate 12 microns of copper.

13. Strip the resist and etch the exposed copper seed layer. This step is shown in Fig. 339.

14. Wafer probe. All electrical connections are complete at this point, bond pads are accessible, and the chips are not yet separated.

15. Deposit 0.1 microns of silicon nitride, which acts as a corrosion barrier (not shown).

16. Deposit 0.1 microns of PTFE (not shown), which makes the top surface of the fixed magnetic plate and the solenoid hydrophobic, thereby preventing the space between the solenoid and the magnetic piston from filling with ink (if a water based ink is used. In general, these surfaces should be made ink-phobic).

17. Etch the PTFE layer using Mask 5. This mask defines the hydrophilic region of the nozzle chamber. The etch returns the nozzle chamber to a hydrophilic state.

18. Deposit 1 micron of sacrificial material. This defines the magnetic gap, and the travel of the magnetic piston.
19. Etch the sacrificial layer using Mask 6. This mask defines the spring posts. This step is shown in Fig. 340.
20. Deposit a seed layer of CoNiFe.
21. Deposit 12 microns of resist. As the solenoids will prevent even flow during a spin-on application, the resist should be sprayed on. Expose the resist using Mask 7, which defines the walls of the magnetic plunger, plus the spring posts. As the resist is thick and the aspect ratio is high, an X-ray proximity process, such as LIGA, can be used. This step is shown in Fig. 341.
22. Electroplate 12 microns of CoNiFe. This step is shown in Fig. 342.
23. Deposit a seed layer of CoNiFe.
24. Spin on 4 microns of resist, expose with Mask 8, and develop. This mask defines the roof of the magnetic plunger, the nozzle, the springs, and the spring posts. The resist forms an electroplating mold for these parts. This step is shown in Fig. 343.
25. Electroplate 3 microns of CoNiFe. This step is shown in Fig. 344.
26. Strip the resist, sacrificial, and exposed seed layers. This step is shown in Fig. 345.
27. Back-etch through the silicon wafer until the nozzle chamber inlet cross is reached using Mask 9. This etch may be performed using an ASE Advanced Silicon Etcher from Surface Technology Systems. The mask defines the ink inlets which are etched through the wafer. The wafer is also diced by this etch. This step is shown in Fig. 346.
28. Mount the print heads in their packaging, which may be a molded plastic former incorporating ink channels which supply the appropriate color ink to the ink inlets at the back of the wafer.
29. Connect the print heads to their interconnect systems. For a low profile connection with minimum disruption of airflow, TAB may be used. Wire bonding may also be used if the printer is to be operated with sufficient clearance to the paper.
30. Fill the completed print heads with ink and test them. A filled nozzle is shown in Fig. 347.

IJ USES

[0031] The presently disclosed ink jet printing technology is potentially suited to a wide range of printing system including: colour and monochrome office printers, short run digital printers, high speed digital printers, offset press supplemental printers, low cost scanning printers high speed pagewidth printers, notebook computers with inbuilt pagewidth printers, portable colour and monochrome printers, colour and monochrome copiers, colour and monochrome facsimile machines, combined printer, facsimile and copying machines, label printers, large format plotters, photograph copiers, printers for digital photographic "minilabs", video printers, PhotoCD printers, portable printers for PDAs, wallpaper printers, indoor sign printers, billboard printers, fabric printers, camera printers and fault tolerant commercial printer arrays.

Ink Jet Technologies

[0032] The embodiments of the invention use an ink jet printer type device. Of course many different devices could be used. However presently popular inkjet printing technologies are unlikely to be suitable.

[0033] The most significant problem with thermal inkjet is power consumption. This is approximately 100 times that required for high speed, and stems from the energy-inefficient means of drop ejection. This involves the rapid boiling of water to produce a vapor bubble which expels the ink. Water has a very high heat capacity, and must be superheated in thermal inkjet applications. This leads to an efficiency of around 0.02%, from electricity input to drop momentum (and increased surface area) out.

[0034] The most significant problem with piezoelectric inkjet is size and cost. Piezoelectric crystals have a very small deflection at reasonable drive voltages, and therefore require a large area for each nozzle. Also, each piezoelectric actuator must be connected to its drive circuit on a separate substrate. This is not a significant problem at the current limit of around 300 nozzles per print head, but is a major impediment to the fabrication of pagewidth print heads with 19,200 nozzles.

[0035] Ideally, the inkjet technologies used meet the stringent requirements of in-camera digital color printing and other high quality, high speed, low cost printing applications. To meet the requirements of digital photography, new inkjet technologies have been created. The target features include:

- low power (less than 10 Watts)
- high resolution capability (1,600 dpi or more)
- photographic quality output
- low manufacturing cost
- small size (pagewidth times minimum cross section)
- high speed (<2 seconds perpage).

[0036] All of these features can be met or exceeded by the inkjet systems described below with differing levels of difficulty. 45 different inkjet technologies have been developed by the Assignee to give a wide range of choices for high volume manufacture. These technologies form part of separate applications assigned to the present Assignee as set out in the table below.

[0037] The inkjet designs shown here are suitable for a wide range of digital printing systems, from battery powered one-time use digital cameras, through to desktop and network printers, and through to commercial printing systems

[0038] For ease of manufacture using standard process equipment, the print head is designed to be a monolithic 0.5 micron CMOS chip with MEMS post processing. For color photographic applications, the print head is 100 mm long with a width which depends upon the inkjet type. The smallest print head designed is IJ38, which is 0.35 mm wide, giving a chip area of 35 square mm. The print heads each contain 19,200 nozzles plus data and control circuitry.

[0039] Ink is supplied to the back of the print head by injection molded plastic ink channels. The molding requires 50 micron features, which can be created using a lithographically micromachined insert in a standard injection molding tool. Ink flows through holes etched through the wafer to the nozzle chambers fabricated on the front surface of the wafer. The print head is connected to the camera circuitry by tape automated bonding.

Cross-Referenced Applications

[0040] The following table is a guide to cross-referenced patent applications filed concurrently herewith and discussed hereinafter with the reference being utilized in subsequent tables when referring to a particular case:

Docket No.	Reference	Title
IJ01US	IJ01	Radiant Plunger Ink Jet Printer
IJ02US	U02	Electrostatic Ink Jet Printer
IJ03US	U03	Planar Thermoelastic Bend Actuator Ink Jet
U04US	IJ04	Stacked Electrostatic Ink Jet Printer
IJ05US	IJ05	Reverse Spring Lever Ink Jet Printer
IJ06US	IJ06	Paddle Type Ink Jet Printer
U07US	U07	Permanent Magnet Electromagnetic Ink Jet Printer
IJ08US	U08	Planar Swing Grill Electromagnetic Ink Jet Printer
U09US	IJ09	Pump Action Refill Ink Jet Printer
IJ10US	IJ10	Pulsed Magnetic Field Ink Jet Printer
IJ11US	IJ11	Two Plate Reverse Firing Electromagnetic Ink Jet Printer
IJ12US	U12	Linear Stepper Actuator Ink Jet Printer
IJ13US	U13	Gear Driven Shutter Ink Jet Printer
IJ14US	IJ14	Tapered Magnetic Pole Electromagnetic Ink Jet Printer
IJ15US	IJ15	Linear Spring Electromagnetic Grill Ink Jet Printer
IJ16US	IJ16	Lorenz Diaphragm Electromagnetic Ink Jet Printer
IJ17US	IJ17	PTFE Surface Shooting Shuttered Oscillating Pressure Ink Jet Printer
IJ18US	IJ18	Buckle Grip Oscillating Pressure Ink Jet Printer
IJ19US	IJ19	Shutter Based Ink Jet Printer
IJ20US	U20	Curling Calyx Thermoelastic Ink Jet Printer
U21US	IJ21	Thermal Actuated Ink Jet Printer
IJ22US	IJ22	Iris Motion Ink Jet Printer
U23US	U23	Direct Firing Thermal Bend Actuator Ink Jet Printer
U24US	U24	Conductive PTFE Ben Activator Vented Ink Jet Printer
IJ25US	IJ25	Magnetostriuctive Ink Jet Printer

(continued)

Docket No.	Reference	Title
IJ26US	U26	Shape Memory Alloy Ink Jet Printer
IJ27US	IJ27	Buckle Plate Ink Jet Printer
IJ28US	IJ28	Thermal Elastic Rotary Impeller Ink Jet Printer
IJ29US	IJ29	Thermoelastic Bend Actuator Ink Jet Printer
U30US	U30	Thermoelastic Bend Actuator Using PTFE and Corrugated Copper Ink Jet Printer
U31US	U31	Bend Actuator Direct Ink Supply Ink Jet Printer
U32US	U32	A High Young's Modulus Thermoelastic Ink Jet Printer
U33US	U33	Thermally actuated slotted chamber wall ink jet printer
IJ34US	IJ34	Ink Jet Printer having a thermal actuator comprising an external coiled spring
U33US	U35	Trough Container Ink Jet Printer
IJ36US	U36	Dual Chamber Single Vertical Actuator Ink Jet
U37US	IJ37	Dual Nozzle Single Horizontal Fulcrum Actuator Ink Jet
IJ38US	IJ38	Dual Nozzle Single Horizontal Actuator Ink Jet
IJ39US	IJ39	A single bend actuator cupped paddle ink jet printing device
IJ40US	U40	A thermally actuated ink jet printer having a series of thermal actuator units
IJ41US	IJ41	A thermally actuated ink jet printer including a tapered heater element
U42US	IJ42	Radial Back-Curling Thermoelastic Ink Jet
IJ43US	IJ43	Inverted Radial Back-Curling Thermoelastic Ink Jet
IJ44US	IJ44	Surface bend actuator vented ink supply ink jet printer
IJ45US	IJ45	Coil Actuated Magnetic Plate Ink Jet Printer

Tables of Drop-on-Demand Inkjets

[0041] Eleven important characteristics of the fundamental operation of individual inkjet nozzles have been identified. These characteristics are largely orthogonal, and so can be elucidated as an eleven dimensional matrix. Most of the eleven axes of this matrix include entries developed by the present assignee.

[0042] The following tables form the axes of an eleven dimensional table of inkjet types.

Actuator mechanism (18 types)
 Basic operation mode (7 types)
 Auxiliary mechanism (8 types)
 Actuator amplification or modification method (17 types)
 Actuator motion (19 types)
 Nozzle refill method (4 types)
 Method of restricting back-flow through inlet (10 types)
 Nozzle clearing method (9 types)
 Nozzle plate construction (9 types)
 Drop ejection direction (5 types)
 Ink type (7 types)

[0043] The complete eleven dimensional table represented by these axes contains 36.9 billion possible configurations of inkjet nozzle. While not all of the possible combinations result in a viable inkjet technology, many million configurations are viable. It is clearly impractical to elucidate all of the possible configurations. Instead, certain inkjet types have been investigated in detail. These are designated IJ01 to IJ45 above.

[0044] Other inkjet configurations can readily be derived from these 45 examples by substituting alternative configu-

rations along one or more of the 11 axes. Most of the IJ01 to IJ45 examples can be made into inkjet print heads with characteristics superior to any currently available inkjet technology.

[0045] Where there are prior art examples known to the inventor, one or more of these examples are listed in the examples column of the tables below. The IJ01 to IJ45 series are also listed in the examples column. In some cases, a printer may be listed more than once in a table, where it shares characteristics with more than one entry.

[0046] Suitable applications include: Home printers, Office network printers, Short run digital printers, Commercial print systems, Fabric printers, Pocket printers, Internet WWW printers, Video printers, Medical imaging, Wide form at printers, Notebook PC printers, Fax machines, Industrial printing systems, Photocopiers, Photographic minilabs etc.

[0047] The information associated with the aforementioned 11 dimensional matrix are set out in the following tables.

Actuator mechanism (applied only to selected ink drops)

[0048]

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Thermal bubble	An electrothermal heater heats the ink to above boiling point, transferring significant heat to the aqueous ink. A bubble nucleates and quickly forms, expelling the ink. The efficiency of the process is low, with typically less than 0.05% of the electrical energy being transformed into kinetic energy of the drop.	◆ Large force generated ◆ Simple construction ◆ No moving parts ◆ Fast operation ◆ Small chip area required for actuator	◆ High power ◆ Ink carrier limited to water ◆ Low efficiency ◆ High temperatures required ◆ High mechanical stress ◆ Unusual materials required ◆ Large drive transistors ◆ Cavitation causes actuator failure ◆ Kogation reduces bubble formation ◆ Large print heads are difficult to fabricate	◆ Canon Bubblejet 1979 Endo et al GB patent 2,007,162 ◆ Xerox heater-in-pit 1990 Hawkins et al USP 4,899,181 ◆ Hewlett-Packard TIJ 1982 Vaught et al USP 4,490,728

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Piezoelectric	A piezoelectric crystal such as lead lanthanum zirconate (PZT) is electrically activated, and either expands, shears, or bends to apply pressure to the ink, ejecting drops.	◆ Low power consumption ◆ Many ink types can be used ◆ Fast operation ◆ High efficiency	◆ Very large area required for actuator ◆ Difficult to integrate with electronics ◆ High voltage drive transistors required ◆ Full pagewidth print heads impractical due to actuator size ◆ Requires electrical poling in high field strengths during manufacture	◆ Kyser et al USP 3,946,398 ◆ Zoltan USP 3,683,212 ◆ 1973 Stemme USP 3,747,120 ◆ Epson Stylus ◆ Tektronix ◆ IJ04
Electro-strictive	An electric field is used to activate electrostriction in relaxor materials such as lead lanthanum zirconate titanate (PLZT) or lead magnesium niobate (PMN).	◆ Low power consumption ◆ Many ink types can be used ◆ Low thermal expansion ◆ Electric field strength required (approx. 3.5 V/μm) can be generated without difficulty ◆ Does not require electrical poling	◆ Low maximum strain (approx. 0.01%) ◆ Large area required for actuator due to low strain ◆ Response speed is marginal ($\sim 10 \mu$s) ◆ High voltage drive transistors required ◆ Full pagewidth print heads impractical due to actuator size	◆ Seiko Epson, Usui et al JP 253401/96 ◆ IJ04
Ferroelectric	An electric field is used to induce a phase transition between the antiferroelectric (AFE) and ferroelectric (FE) phase. Perovskite materials such as tin modified lead lanthanum zirconate titanate (PLZSnT) exhibit large strains of up to 1% associated with the AFE to FE phase transition.	◆ Low power consumption ◆ Many ink types can be used ◆ Fast operation ($< 1 \mu$s) ◆ Relatively high longitudinal strain ◆ High efficiency ◆ Electric field strength of around 3 V/μm can be readily provided	◆ Difficult to integrate with electronics ◆ Unusual materials such as PLZSnT are required ◆ Actuators require a large area	◆ IJ04

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Electrostatic plates	Conductive plates are separated by a compressible or fluid dielectric (usually air). Upon application of a voltage, the plates attract each other and displace ink, causing drop ejection. The conductive plates may be in a comb or honeycomb structure, or stacked to increase the surface area and therefore the force.	◆ Low power consumption ◆ Many ink types can be used ◆ Fast operation	◆ Difficult to operate electrostatic devices in an aqueous environment ◆ The electrostatic actuator will normally need to be separated from the ink ◆ Very large area required to achieve high forces ◆ High voltage drive transistors may be required ◆ Full pagewidth print heads are not competitive due to actuator size	◆ IJ02, IJ04
Electrostatic pull on ink	A strong electric field is applied to the ink, whereupon electrostatic attraction accelerates the ink towards the print medium.	◆ Low current consumption ◆ Low temperature	◆ High voltage required ◆ May be damaged by sparks due to air breakdown ◆ Required field strength increases as the drop size decreases ◆ High voltage drive transistors required ◆ Electrostatic field attracts dust	◆ 1989 Saito et al, USP 4,799,068 ◆ 1989 Miura et al, USP 4,810,954 ◆ Tone-jet

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Permanent magnet electromagnetic	An electromagnet directly attracts a permanent magnet, displacing ink and causing drop ejection. Rare earth magnets with a field strength around 1 Tesla can be used. Examples are: Samarium Cobalt (SaCo) and magnetic materials in the neodymium iron boron family (NdFeB, NdDyFeBNb, NdDyFeB, etc)	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation ♦ High efficiency ♦ Easy extension from single nozzles to pagewidth print heads	♦ Complex fabrication ♦ Permanent magnetic material such as Neodymium Iron Boron (NdFeB) required. ♦ High local currents required ♦ Copper metalization should be used for long electromigration lifetime and low resistivity ♦ Pigmented inks are usually infeasible Curie temperature (around 540 K)	♦ IJ07, IJ10
Soft magnetic core electro-magnetic	A solenoid induced a magnetic field in a soft magnetic core or yoke fabricated from a ferrous material such as electroplated iron alloys such as CoNiFe [1], CoFe, or NiFe alloys. Typically, the soft magnetic material is in two parts, which are normally held apart by a spring. When the solenoid is actuated, the two parts attract, displacing the ink.	♦ Low power consumption ♦ Many Ink types can be used ♦ Fast operation ♦ High efficiency ♦ Easy extension from single nozzles to pagewidth print heads	♦ Complex fabrication ♦ Materials not usually present in a CMOS fab such as NiFe, CoNiFe, or CoFe are required ♦ High local currents required ♦ Copper metalization should be used for long electromigration lifetime and low resistivity ♦ Electroplating is required ♦ High saturation flux density is required (2.0-2.1 T is achievable with CoNiFe [1])	♦ IJ01, IJ05, IJ08, IJ10 ♦ IJ12, IJ14, IJ15, IJ17

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Magnetic Lorentz force	The Lorentz force acting on a current carrying wire in a magnetic field is utilized. This allows the magnetic field to be supplied externally to the print head, for example with rare earth permanent magnets. Only the current carrying wire need be fabricated on the print-head, simplifying materials requirements.	♦ Low power consumption ♦ Many ink types can be used ♦ Fast operation ♦ High efficiency ♦ Easy extension from single nozzles to pagewidth print heads	♦ Force acts as a twisting motion ♦ Typically, only a quarter of the solenoid length provides force in a useful direction ♦ High local currents required ♦ Copper metalization should be used for long electromigration lifetime and low resistivity ♦ Pigmented inks are usually infeasible	♦ IJ06, IJ11, IJ13, IJ16
Magneto-striction	The actuator uses the giant magnetostrictive effect of materials such as Terfenol-D (an alloy of terbium, dysprosium and iron developed at the Naval Ordnance Laboratory, hence Ter-Fe-NOL). For best efficiency, the actuator should be pre-stressed to approx, 8 MPa.	♦ Many ink types can be used ♦ Fast operation ♦ Easy extension from single nozzles to pagewidth print heads ♦ High force is available	♦ Force acts as a twisting motion ♦ Unusual materials such as Terfenol-D are required ♦ High local currents required ♦ Copper metalization should be used for long electromigration lifetime and low resistivity ♦ Pre-stressing may be required	♦ Fischenbeck, USP 4,032,929 ♦ IJ25

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Surface tension reduction	Ink under positive pressure is held in a nozzle by surface tension. The surface tension of the ink is reduced below the bubble threshold, causing the ink to egress from the nozzle.	◆ Low power consumption ◆ Simple construction ◆ No unusual materials required in fabrication ◆ High efficiency ◆ Easy extension from single nozzles to pagewidth print heads	◆ Requires supplementary force to effect drop separation ◆ Requires special ink surfactants ◆ Speed may be limited by surfactant properties	◆ Silverbrook, EP 0771 658 A2 and related patent applications
Viscosity reduction	The ink viscosity is locally reduced to select which drops are to be ejected. A viscosity reduction can be achieved electrothermally with most inks, but special inks can be engineered for a 100:1 viscosity reduction.	◆ Simple construction ◆ No unusual materials required in fabrication ◆ Easy extension from single nozzles to pagewidth print heads	◆ Requires supplementary force to effect drop separation ◆ Requires special ink viscosity properties ◆ High speed is difficult to achieve ◆ Requires oscillating ink pressure ◆ A high temperature difference (typically 80 degrees) is required	◆ Silverbrook, EP 0771 658 A2 and related patent applications
Acoustic	An acoustic wave is generated and focussed upon the drop ejection region.	◆ Can operate without a nozzle plate	◆ Complex drive circuitry ◆ Complex fabrication ◆ Low efficiency ◆ Poor control of drop position ◆ Poor control of drop volume	◆ 1993 Hadimioglu et al, EUP 550,192 ◆ 1993 Elrod et al, EUP 572,220

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Thermoelastic bend actuator	An actuator which relies upon differential thermal expansion upon Joule heating is used.	◆ Low power consumption ◆ Many ink types can be used ◆ Simple planar fabrication ◆ Small chip area required for each actuator ◆ Fast operation ◆ High efficiency ◆ CMOS compatible voltages and currents ◆ Standard MEMS processes can be used ◆ Easy extension from single nozzles to pagewidth print heads	◆ Efficient aqueous operation requires a thermal insulator on the hot side ◆ Corrosion prevention can be difficult ◆ Pigmented inks may be infeasible, as pigment particles may jam the bend actuator	◆ IJ03, IJ09, IJ17, IJ18 ◆ IJ19, IJ20, IJ21, IJ22 ◆ IJ23, IJ24, IJ27, IJ28 ◆ IJ29, IJ30, U31, U32 ◆ IJ33, IJ34, IJ35, U36 ◆ IJ37, IJ38, IJ39, IJ40 ◆ IJ41
High CTE	A material with a very high coefficient of thermal expansion (CTE) such as polytetrafluoroethylene (PTFE) is used. As high CTE materials are usually non-conductive, a heater fabricated from a conductive material is incorporated. A 50 μm long PTFE bend actuator with polysilicon heater and 15 mW power input can provide 180 μN force and 10 μm deflection. Actuator motions include:	◆ High force can be generated	◆ Requires special material (e.g. PTFE)	◆ IJ09, IJ17, IJ18, IJ20

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
thermoelastic actuator	1) Bend	♦ PTFE is a candidate for low dielectric constant insulation in ULSI	♦ Requires a PTFE deposition process, which is not yet standard in ULSI fabs	♦ IJ21, IJ22, IJ23, IJ24
	2) Push	♦ Very low power consumption	♦ PTFE deposition cannot be followed with high temperature (above 350 °C) processing	♦ IJ27, IJ28, IJ29, IJ30
	3) Buckle	♦ Many ink types can be used	♦ Pigmented inks may be infeasible, as pigment particles may jam the bend actuator	♦ IJ31, IJ42, IJ43, IJ44
	4) Rotate	♦ Simple planar fabrication ♦ Small chip area required for each actuator ♦ Fast operation ♦ High efficiency ♦ CMOS compatible voltages and currents ♦ Easy extension from single nozzles to pagewidth print heads		

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Conductive polymer thermoelastic actuator	A polymer with a high coefficient of thermal expansion (such as PTFE) is doped with conducting substances to increase its conductivity to about 3 orders of magnitude below that of copper. The conducting polymer expands when resistively heated. Examples of conducting dopants include: 1) Carbon nanotubes 2) Metal fibers 3) Conductive polymers such as doped polythiophene 4) Carbon granules	◆ High force can be generated ◆ Very low power consumption ◆ Many ink types can be used ◆ Simple planar fabrication ◆ Small chip area required for each actuator ◆ Fast operation ◆ High efficiency ◆ CMOS compatible voltages and currents ◆ Easy extension from single nozzles to pagewidth print heads	◆ Requires special materials development (High CTE conductive polymer) ◆ Requires a PTFE deposition process, which is not yet standard in ULSI fabs ◆ PTFE deposition cannot be followed with high temperature (above 350 °C) processing ◆ Evaporation and CVD deposition techniques cannot be used ◆ Pigmented inks may be infeasible, as pigment particles may jam the bend actuator	◆ IJ24

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
Shape memory alloy	A shape memory alloy such as TiNi (also known as Nitinol - Nickel Titanium alloy developed at the Naval Ordnance Laboratory) is thermally switched between its weak martensitic state and its high stiffness austenitic state. The shape of the actuator in its martensitic state is deformed relative to the austenitic shape. The shape change causes ejection of a drop.	◆ High force is available (stresses of hundreds of MPa) ◆ Large strain is available (more than 3%) ◆ High corrosion resistance ◆ Simple construction ◆ Easy extension from single nozzles to pagewidth print heads ◆ Low voltage operation	◆ Fatigue limits maximum number of cycles ◆ Low strain (1%) is required to extend fatigue resistance ◆ Cycle rate limited by heat removal ◆ Requires unusual materials (TiNi) ◆ The latent heat of transformation must be provided ◆ High current operation ◆ Requires pre-stressing to distort the martensitic state	◆ IJ26
Linear Magnetic Actuator	Linear magnetic actuators Include the Linear Induction Actuator (LIA), Linear Permanent Magnet Synchronous Actuator (LPMSA), Linear Reluctance Synchronous Actuator (LRSA), Linear Switched Reluctance Actuator (LSRA), and the Linear Stepper Actuator (LSA).	◆ Linear Magnetic actuators can be constructed with high thrust, long travel, and high efficiency using planar semiconductor fabrication techniques ◆ Long actuator travel is available ◆ Medium force is available ◆ Low voltage operation	◆ Requires unusual semiconductor materials such as soft magnetic alloys (e.g. CoNiFe [1]) ◆ Some varieties also require permanent magnetic materials such as Neodymium iron boron (NdFeB) ◆ Requires complex multi-phase drive circuitry ◆ High current operation	◆ IJ12

Basic operation mode**[0049]**

Operational mode	Description	Advantages	Disadvantages	Examples
Actuator directly pushes ink	This is the simplest mode of operation: the actuator directly supplies sufficient kinetic energy to expel the drop. The drop must have a sufficient velocity to overcome the surface tension.	◆ Simple operation. ◆ No external fields required ◆ Satellite drops can be avoided if drop velocity is less than 4 m/s ◆ Can be efficient, depending upon the actuator used	◆ Drop repetition rate is usually limited to less than 10 KHz. However, this is not fundamental to the method, but is related to the refill method normally used ◆ All of the drop kinetic energy must be provided by the actuator ◆ Satellite drops usually form if drop velocity is greater than 4.5 m/s	◆ Thermal inkjet ◆ Piezoelectric inkjet ◆ IJ01, IJ02, IJ03, IJ04 ◆ IJ05, IJ06, IJ07, IJ09 ◆ IJ11, IJ12, IJ14, IJ16 ◆ IJ20, IJ22, IJ23, IJ24 ◆ IJ25, IJ26, IJ27, IJ28 ◆ IJ29, IJ30, IJ31, IJ32 ◆ IJ33, IJ34, IJ35, IJ36 ◆ IJ37, IJ38, IJ39, IJ40 ◆ IJ41, IJ42, IJ43, IJ44
Proximity	The drops to be printed are selected by some manner (e.g. thermally induced surface tension reduction of pressurized ink). Selected drops are separated from the ink in the nozzle by contact with the print medium or a transfer roller.	◆ Very simple print head fabrication can be used ◆ The drop selection means does not need to provide the energy required to separate the drop from the nozzle	◆ Requires close proximity between the print head and the print media or transfer roller ◆ May require two print heads printing alternate rows of the image ◆ Monolithic color print heads are difficult	◆ Silverbrook, EP 0771 658 A2 and related patent applications

(continued)

Operational mode	Description	Advantages	Disadvantages	Examples
Electrostatic pull on ink	The drops to be printed are selected by some manner (e.g. thermally induced surface tension reduction of pressurized ink). Selected drops are separated from the ink in the nozzle by a strong electric field.	♦ Very simple print head fabrication can be used ♦ The drop selection means does not need to provide the energy required to separate the drop from the nozzle	♦ Requires very high electrostatic field ♦ Electrostatic field for small nozzle sizes is above air breakdown ♦ Electrostatic field may attract dust	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Tone-Jet
Magnetic pull on ink	The drops to be printed are selected by some manner (e.g. thermally induced surface tension reduction of pressurized ink). Selected drops are separated from the ink in the nozzle by a strong magnetic field acting on the magnetic ink.	♦ Very simple print head fabrication can be used ♦ The drop selection means does not need to provide the energy required to separate the drop from the nozzle	♦ Requires magnetic ink ♦ Ink colors, other than black are difficult ♦ Requires very high magnetic fields	♦ Silverbrook, EP 0771 658 A2 and related patent applications
Shutter	The actuator moves a shutter to block ink flow to the nozzle. The ink pressure is pulsed at a multiple of the drop ejection frequency.	♦ High speed (>50 KHz) operation can be achieved due to reduced refill time ♦ Drop timing can be very accurate ♦ The actuator energy can be very low	♦ Moving parts are required ♦ Requires ink pressure modulator ♦ Friction and wear must be considered ♦ Stiction is possible	♦ IJ13, IJ17, IJ21
Shuttered grill	The actuator moves a shutter to block ink flow through a grill to the nozzle. The shutter movement need only be equal to the width of the grill holes.	♦ Actuators with small travel can be used ♦ Actuators with small force can be used ♦ High speed (>50 KHz) operation can be achieved	♦ Moving parts are required ♦ Requires ink pressure modulator ♦ Friction and wear must be considered ♦ Stiction is possible	♦ IJ08, IJ15, IJ18, IJ19

(continued)

Operational mode	Description	Advantages	Disadvantages	Examples
Pulsed magnetic pull on ink pusher	A pulsed magnetic field attracts an 'ink pusher' at the drop ejection frequency. An actuator controls a catch, which prevents the ink pusher from moving when a drop is not to be ejected.	♦ Extremely low energy operation is possible ♦ No heat dissipation problems	♦ Requires an external pulsed magnetic field ♦ Requires special materials for both the actuator and the ink pusher ♦ Complex construction	♦ IJ10

Auxillary mechanism (applied to all nozzles)**[0050]**

Auxillary Mechanism	Description	Advantages	Disadvantages	Examples
None	The actuator directly fires the ink drop, and there is no external field or other mechanism required.	♦ Simplicity of construction ♦ Simplicity of operation ♦ Small physical size	♦ Drop ejection energy must be supplied by individual nozzle actuator	♦ Most inkjets, including piezoelectric and thermal bubble. ♦ IJ01- IJ07, IJ09, IJ11 ♦ IJ12, IJ14, U20, IJ22 ♦ IJ23-IJ45
Oscillating ink pressure (including acoustic stimulation)	The ink pressure oscillates, providing much of the drop ejection energy. The actuator selects which drops are to be fired by selectively blocking or enabling nozzles. The ink pressure oscillation may be achieved by vibrating the print head, or preferably by an actuator in the ink supply.	♦ Oscillating ink pressure can provide a refill pulse, allowing higher operating speed ♦ The actuators may operate with much lower energy ♦ Acoustic lenses can be used to focus the sound on the nozzles	♦ Requires external ink pressure oscillator ♦ Ink pressure phase and amplitude must be carefully controlled ♦ Acoustic reflections in the ink chamber must be designed for	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ IJ08, IJ13, IJ15, IJ17 ♦ IJ18, IJ19, IJ21

(continued)

Auxiliary Mechanism	Description	Advantages	Disadvantages	Examples
Media proximity	The print head is placed in close proximity to the print medium. Selected drops protrude from the print head further than unselected drops, and contact the print medium. The drop soaks into the medium fast enough to cause drop separation.	♦ Low power ♦ High accuracy ♦ Simple print head construction	♦ Precision assembly required ♦ Paper fibers may cause problems ♦ Cannot print on rough substrates	♦ Silverbrook, EP 0771 658 A2 and related patent applications
Transfer roller	Drops are printed to a transfer roller instead of straight to the print medium. A transfer roller can also be used for proximity drop separation.	♦ High accuracy ♦ Wide range of print substrates can be used ♦ Ink can be dried on the transfer roller	♦ Bulky ♦ Expensive ♦ Complex construction	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Tektronix hot melt piezoelectric inkjet ♦ Any of the U series
Electrostatic	An electric field is used to accelerate selected drops towards the print medium.	♦ Low power ♦ Simple print head construction	♦ Field strength required for separation of small drops is near or above air breakdown	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Tone-Jet
Direct magnetic field	A magnetic field is used to accelerate selected drops of magnetic ink towards the print medium.	♦ Low power ♦ Simple print head construction	♦ Requires magnetic ink ♦ Requires strong magnetic field	♦ Silverbrook, EP 0771 658 A2 and related patent applications
Cross magnetic field	The print head is placed in a constant magnetic field. The Lorentz force in a current carrying wire is used to move the actuator.	♦ Does not require magnetic materials to be integrated in the print head manufacturing process	♦ Requires external magnet ♦ Current densities may be high, resulting in electromigration problems	♦ IJ06, IJ16

(continued)

Auxiliary Mechanism	Description	Advantages	Disadvantages	Examples
Pulsed magnetic field	A pulsed magnetic field is used to cyclically attract a paddle, which pushes on the ink. A small actuator moves a catch, which selectively prevents the paddle from moving.	♦ Very low power operation is possible ♦ Small print head size	♦ Complex print head construction ♦ Magnetic materials required in print head	♦ IJ10

Actuator amplification or modification method**[0051]**

Actuator amplification	Description	Advantages	Disadvantages	Examples
None	No actuator mechanical amplification is used. The actuator directly drives the drop ejection process.	♦ Operational simplicity	♦ Many actuator mechanisms have insufficient travel, or insufficient force, to efficiently drive the drop ejection process	♦ Thermal Bubble Inkjet ♦ IJ01, IJ02, IJ06, IJ07 ♦ IJ16, IJ25, IJ26
Differential expansion bend actuator	An actuator material expands more on one side than on the other. The expansion may be thermal, piezoelectric, magnetostrictive, or other mechanism.	♦ Provides greater travel in a reduced print head area ♦ The bend actuator converts a high force low travel actuator mechanism to high travel, lower force mechanism.	♦ High stresses are involved ♦ Care must be taken that the materials do not delaminate ♦ Residual bend resulting from high temperature or high stress during formation	♦ Piezoelectric ♦ IJ03, IJ09, IJ17-IJ24 ♦ IJ27, IJ29-IJ39, IJ42, IJ43, U44
Transient bend actuator	A trilayer bend actuator where the two outside layers are identical. This cancels bend due to ambient temperature and residual stress. The actuator only responds to transient heating of one side or the other.	♦ Very good temperature stability ♦ High speed, as a new drop can be fired before heat dissipates ♦ Cancels residual stress of formation	♦ High stresses are involved ♦ Care must be taken that the materials do not delaminate	♦ IJ40, IJ41

(continued)

Actuator amplification	Description	Advantages	Disadvantages	Examples
Actuator stack	A series of thin actuators are stacked. This can be appropriate where actuators require high electric field strength, such as electrostatic and piezoelectric actuators.	◆ Increased travel ◆ Reduced drive voltage	◆ Increased fabrication complexity ◆ Increased possibility of short circuits due to pinholes	◆ Some piezoelectric ink jets ◆ IJ04
Multiple actuators	Multiple smaller actuators are used simultaneously to move the ink. Each actuator need provide only a portion of the force required,	◆ Increases the force available from an actuator ◆ Multiple actuators can be positioned to control ink flow accurately	◆ Actuator forces may not add linearly, reducing efficiency	◆ IJ12, IJ13, IJ18, U20 ◆ IJ22, IJ28, IJ42, U43
Linear Spring	A linear spring is used to transform a motion with small travel and high force into a longer travel, lower force motion.	◆ Matches low travel actuator with higher travel requirements ◆ Non-contact method of motion transformation	◆ Requires print head area for the spring	◆ IJ15
Reverse spring	The actuator loads a spring. When the actuator is turned off, the spring releases. This can reverse the force/ distance curve of the actuator to make it compatible with the force/time requirements of the drop ejection.	◆ Better coupling to the ink	◆ Fabrication complexity ◆ High stress in the spring	◆ IJ05, IJ11
Coiled actuator	A bend actuator is coiled to provide greater travel in a reduced chip area.	◆ Increases travel ◆ Reduces chip area ◆ Planar implementations are relatively easy to fabricate.	◆ Generally restricted to planar implementations due to extreme fabrication difficulty in other	◆ IJ17, IJ21, U34, IJ35

(continued)

Actuator amplification	Description	Advantages	Disadvantages	Examples
Flexure bend actuator	A bend actuator has a small region near the fixture point, which flexes much more readily than the remainder of the actuator. The actuator flexing is effectively converted from an even coiling to an angular bend, resulting in greater travel of the actuator tip.	◆ Simple means of increasing travel of a bend actuator	◆ Care must be taken not to exceed the elastic limit in the flexure area ◆ Stress distribution is very uneven ◆ Difficult to accurately model with finite element analysis	◆ IJ10, IJ19, U33
Gears	Gears can be used to increase travel at the expense of duration. Circular gears, rack and pinion, ratchets, and other gearing methods can be used.	◆ Low force, low travel actuators can be used ◆ Can be fabricated using standard surface MEMS processes	◆ Moving parts are required ◆ Several actuator cycles are required ◆ More complex drive electronics ◆ Complex construction ◆ Friction, friction, and wear are possible	◆ IJ13
Catch	The actuator controls a small catch. The catch either enables or disables movement of an ink pusher that is controlled in a bulk manner.	◆ Very low actuator energy ◆ Very small actuator size	◆ Complex construction ◆ Requires external force ◆ Unsuitable for pigmented inks	◆ IJ10
Buckle plate	A buckle plate can be used to change a slow actuator into a fast motion. It can also convert a high force, low travel actuator into a high travel, medium force motion.	◆ Very fast movement achievable	◆ Must stay within elastic limits of the materials for long device life ◆ High stresses involved ◆ Generally high power requirement	◆ S. Hirata et al, "An Ink-jet Head ...", Proc. IEEE MEMS, Feb. 1996, pp 418-423. ◆ IJ18, IJ27
Tapered magnetic pole	A tapered magnetic pole can increase travel at the expense of force.	◆ Linearizes the magnetic force/distance curve	◆ Complex construction	◆ IJ14

(continued)

Actuator amplification	Description	Advantages	Disadvantages	Examples
Lever	A lever and fulcrum is used to transform a motion with small travel and high force into a motion with longer travel and lower force. The lever can also reverse the direction of travel.	◆ Matches low travel actuator with higher travel requirements ◆ Fulcrum area has no linear movement, and can be used for a fluid seal	◆ High stress around the fulcrum	◆ IJ32, IJ36, IJ37
Rotary impeller	The actuator is connected to a rotary impeller. A small angular deflection of the actuator results in a rotation of the impeller vanes, which push the ink against stationary vanes and out of the nozzle.	◆ High mechanical advantage ◆ The ratio of force to travel of the actuator can be matched to the nozzle requirements by varying the number of impeller vanes	◆ Complex construction ◆ Unsuitable for pigmented inks	◆ IJ28
Acoustic lens	A refractive or diffractive (e.g. zone plate) acoustic lens is used to concentrate sound waves.	◆ No moving parts	◆ Large area required ◆ Only relevant for acoustic ink jets	◆ 1993 Hadimioglu et al, EUP 550,192 ◆ 1993 Elrod et al, EUP 572,220
Sharp conductive point	A sharp point is used to concentrate an electrostatic field.	◆ Simple construction	◆ Difficult to fabricate using standard VLSI processes for a surface ejecting ink-jet ◆ Only relevant for electrostatic ink jets	◆ Tone-jet

Actuator motion

[0052]

Actuator motion	Description	Advantages	Disadvantages	Examples
Volume expansion	The volume of the actuator changes, pushing the ink in all directions.	◆ Simple construction in the case of thermal ink jet	◆ High energy is typically required to achieve volume expansion. This leads to thermal stress, cavitation, and kagation in thermal ink jet implementations	◆ Hewlett-Packard Thermal Inkjet ◆ Canon Bubblejet

(continued)

Actuator motion	Description	Advantages	Disadvantages	Examples
Linear, normal to chip surface	The actuator moves in a direction normal to the print head surface. The nozzle is typically in the line of movement	♦ Efficient coupling to ink drops ejected normal to the surface	♦ High fabrication complexity may be required to achieve perpendicular motion	♦ IJ01, IJ02, IJ04, IJ07 ♦ IJ11, IJ14
Linear, parallel to chip surface	The actuator moves parallel to the print head surface. Drop ejection may still be normal to the surface.	♦ Suitable for planar fabrication	♦ Fabrication complexity ♦ Friction ♦ Stiction	♦ IJ12, U13, IJ15, U33, ♦ IJ34, U35, IJ36
Membrane push	An actuator with a high force but small area is used to push a stiff membrane that is in contact with the ink.	♦ The effective area of the actuator becomes the membrane area	♦ Fabrication complexity ♦ Actuator size ♦ Difficulty of integration in a VLSI process	♦ 1982 Howkins USP 4,459,601
Rotary	The actuator causes the rotation of some element, such a grill or impeller	♦ Rotary levers may be used to increase travel ♦ Small chip area requirements	♦ Device complexity ♦ May have friction at a pivot point	♦ IJ05, IJ08, IJ13, IJ28
Bend	The actuator bends when energized. This may be due to differential thermal expansion, piezoelectric expansion, magnetostriction, or other form of relative dimensional change.	♦ A very small change in dimensions can be converted to a large motion.	♦ Requires the actuator to be made from at least two distinct layers, or to have a thermal difference across the actuator	♦ 1970 Kyser et al USP 3,946,398 ♦ 1973 Stemme USP 3,747,120 ♦ IJ03, IJ09, IJ10, IJ19 ♦ IJ23, IJ24, IJ25, U29 ♦ IJ30, IJ31, IJ33, IJ34 ♦ IJ35
Swivel	The actuator swivels around a central pivot. This motion is suitable where there are opposite forces applied to opposite sides of the paddle, e.g. Lorenz force.	♦ Allows operation where the net linear force on the paddle is zero ♦ Small chip area requirements	♦ Inefficient coupling to the ink motion	♦ IJ06
Straighten	The actuator is normally bent, and straightens when energized.	♦ Can be used with shape memory alloys where the austenitic phase is planar	♦ Requires careful balance of stresses to ensure that the quiescent bend is accurate	♦ U26, U32

(continued)

Actuator motion	Description	Advantages	Disadvantages	Examples
Double bend	The actuator bends in one direction when one element is energized, and bends the other way when another element is energized.	♦ One actuator can be used to power two nozzles, ♦ Reduced chip size. ♦ Not sensitive to ambient temperature	♦ Difficult to make the drops ejected by both bend directions identical. ♦ A small efficiency loss compared to equivalent single bend actuators.	♦ IJ36, IJ37, IJ38
Shear	Energizing the actuator causes a shear motion in the actuator material.	♦ Can increase the effective travel of piezoelectric actuators	♦ Not readily applicable to other actuator mechanisms	♦ 1985 Fishbeck USP 4,584,590
Radial constriction	The actuator squeezes an ink reservoir, forcing ink from a constricted nozzle.	♦ Relatively easy to fabricate single nozzles from glass tubing as macroscopic structures	♦ High force required ♦ Inefficient ♦ Difficult to integrate with VLSI processes	♦ 1970 Zoltan USP 3,683,212
Coil / uncoil	A coiled actuator uncoils or coils more tightly. The motion of the free end of the actuator ejects the ink.	♦ Easy to fabricate as a planar VLSI process ♦ Small area required, therefore low cost	♦ Difficult to fabricate for non-planar devices ♦ Poor out-of-plane stiffness	♦ IJ17, IJ21, IJ34, IJ35
Bow	The actuator bows (or buckles) in the middle when energized.	♦ Can increase the speed of travel ♦ Mechanically rigid	♦ Maximum travel is constrained ♦ High force required	♦ IJ16, IJ18, IJ27
Push-Pull	Two actuators control a shutter. One actuator pulls the shutter, and the other pushes it.	♦ The structure is pinned at both ends, so has a high out-of-plane rigidity	♦ Not readily suitable for inkjets which directly push the ink	♦ IJ18
Curl inwards	A set of actuators curl inwards to reduce the volume of ink that they enclose.	♦ Good fluid flow to the region behind the actuator increases efficiency	♦ Design complexity	♦ IJ20, IJ42
Curl outwards	A set of actuators curl outwards, pressurizing ink in a chamber surrounding the actuators, and expelling ink from a nozzle in the chamber.	♦ Relatively simple construction	♦ Relatively large chip area	♦ IJ43

(continued)

Actuator motion	Description	Advantages	Disadvantages	Examples
Iris	Multiple vanes enclose a volume of ink. These simultaneously rotate, reducing the volume between the vanes.	♦ High efficiency ♦ Small chip area	♦ High fabrication complexity ♦ Not suitable for pigmented inks	♦ IJ22
Acoustic vibration	The actuator vibrates at a high frequency.	♦ The actuator can be physically distant from the ink	♦ Large area required for efficient operation at useful frequencies ♦ Acoustic coupling and crosstalk ♦ Complex drive circuitry ♦ Poor control of drop volume and position	♦ 1993 Hadimioglu et al, EUP 550,192 ♦ 1993 Elrod et al, EUP 572,220
None	In various inkjet designs the actuator does not move.	♦ No moving parts	♦ Various other tradeoffs are required to eliminate moving parts	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Tone-jet

Nozzle refill method**[0053]**

Nozzle refill method	Description	Advantages	Disadvantages	Examples
Surface tension	After the actuator is energized, it typically returns rapidly to its normal position. This rapid return sucks in air through the nozzle opening. The ink surface tension at the nozzle then exerts a small force restoring the meniscus to a minimum area.	♦ Fabrication simplicity ♦ Operational simplicity	♦ Low speed ♦ Surface tension force relatively small compared to actuator force ♦ Long refill time usually dominates the total repetition rate	♦ Thermal inkjet ♦ Piezoelectric inkjet ♦ IJ01-IJ07, IJ10-IJ14 ♦ IJ16, IJ20, IJ22-IJ45

(continued)

Nozzle refill method	Description	Advantages	Disadvantages	Examples
Shuttered oscillating ink pressure	Ink to the nozzle chamber is provided at a pressure that oscillates at twice the drop ejection frequency. When a drop is to be ejected, the shutter is opened for 3 half cycles: drop ejection, actuator return, and refill.	◆ High speed ◆ Low actuator energy, as the actuator need only open or close the shutter. instead of ejecting the ink drop	◆ Requires common ink pressure oscillator ◆ May not be suitable for pigmented inks	◆ IJ08, IJ13, IJ15, IJ17 ◆ IJ18, IJ19, IJ21
Refill actuator	After the main actuator has ejected a drop a second (refill) actuator is energized. The refill actuator pushes ink into the nozzle chamber. The refill actuator returns slowly, to prevent its return from emptying the chamber again.	◆ High speed, as the nozzle is actively refilled	◆ Requires two independent actuators per nozzle	◆ IJ09
Positive ink pressure	The ink is held a slight positive pressure. After the ink drop is ejected, the nozzle chamber fills quickly as surface tension and ink pressure both operate to refill the nozzle.	◆ High refill rate, therefore a high drop repetition rate is possible	◆ Surface spill must be prevented ◆ Highly hydrophobic print head surfaces are required	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ Alternative for: ◆ IJ01-IJ07, IJ10-IJ14 ◆ IJ16, IJ20, IJ22-IJ45

Method of restricting back-flow through inlet

[0054]

Inlet back-flow restriction method	Description	Advantages	Disadvantages	Examples
Long inlet channel	The ink inlet channel to the nozzle chamber is made long and relatively narrow, relying on viscous drag to reduce inlet back-flow.	◆ Design simplicity	◆ Restricts refill rate	◆ Thermal inkjet

(continued)

Inlet back-flow restriction method	Description	Advantages	Disadvantages	Examples
		◆ Operational simplicity ◆ Reduces crosstalk	◆ May result in a relatively large chip area ◆ Only partially effective	◆ Piezoelectric inkjet ◆ IJ42, IJ43
Positive ink pressure	The ink is under a positive pressure, so that in the quiescent state some of the ink drop already protrudes from the nozzle. This reduces the pressure in the nozzle chamber which is required to eject a certain volume of ink. The reduction in chamber pressure results in a reduction in ink pushed out through the inlet.	◆ Drop selection and separation forces can be reduced ◆ Fast refill time	◆ Requires a method (such as a nozzle rim or effective hydrophobizing, or both) to prevent flooding of the ejection surface of the print head.	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ Possible operation of the following: ◆ IJ01-IJ07, U09- IJ12 ◆ IJ14, IJ16, IJ20, U22, IJ23-IJ34, U36-IJ41 ◆ IJ44
Baffle	One or more baffles are placed in the inlet ink flow. When the actuator is energized, the rapid ink movement creates eddies which restrict the flow through the inlet. The slower refill process is unrestricted, and does not result in eddies.	◆ The refill rate is not as restricted as the long inlet method. ◆ Reduces crosstalk	◆ Design complexity ◆ May increase fabrication complexity (e.g. Tektronix hot melt Piezoelectric print heads).	◆ HP Thermal Ink Jet ◆ Tektronix piezoelectric ink jet
Flexible flap restricts inlet	In this method recently disclosed by Canon, the expanding actuator (bubble) pushes on a flexible flap that restricts the inlet.	◆ Significantly reduces back-flow for edge-shooter thermal ink jet devices	◆ Not applicable to most inkjet configurations ◆ Increased fabrication complexity ◆ Inelastic deformation of polymer flap results in creep over extended use	◆ Canon

(continued)

Inlet back-flow restriction method	Description	Advantages	Disadvantages	Examples
Inlet filter	A filter is located between the ink inlet and the nozzle chamber. The filter has a multitude of small holes or slots, restricting ink flow. The filter also removes particles which may block the nozzle.	◆ Additional advantage of ink filtration ◆ Ink filter may be fabricated with no additional process steps	◆ Restricts refill rate ◆ May result in complex construction	◆ IJ04, U 12, IJ24, IJ27 ◆ IJ29, U30
Small Inlet compared to nozzle	The ink inlet channel to the nozzle chamber has a substantially smaller cross section than that of the nozzle, resulting in easier ink egress out of the nozzle than out of the inlet.	◆ Design simplicity	◆ Restricts refill rate ◆ May result in a relatively large chip area ◆ Only partially effective	◆ IJ02, IJ37, IJ44
Inlet shutter	A secondary actuator controls the position of a shutter, closing off the ink inlet when the main actuator is energized.	◆ Increases speed of the ink-jet print head operation	◆ Requires separate refill actuator and drive circuit	◆ IJ09
The inlet is located behind the ink-pushing surface	The method avoids the problem of inlet back-flow by arranging the ink-pushing surface of the actuator between the inlet and the nozzle.	◆ Back-flow problem is eliminated	◆ Requires careful design to minimize the negative pressure behind the paddle	◆ IJ01, IJ03, IJ05, U06 ◆ IJ07, IJ10, IJ11, IJ14 ◆ IJ 16, IJ22, IJ23, IJ25 ◆ IJ28, IJ31, IJ32, IJ33 ◆ IJ34, U35, U36, IJ39 ◆ IJ40, IJ41
Part of the actuator moves to shut off the inlet	The actuator and a wall of the ink chamber are arranged so that the motion of the actuator closes off the inlet.	◆ Significant reductions in back-flow can be achieved ◆ Compact designs possible	◆ Small increase in fabrication complexity	◆ IJ07, IJ20, IJ26, IJ38

(continued)

Inlet back-flow restriction method	Description	Advantages	Disadvantages	Examples
Nozzle actuator does not result in ink back-flow	In some configurations of ink jet, there is no expansion or movement of an actuator which may cause ink back-flow through the inlet.	♦ Ink back-flow problem is eliminated	♦ None related to ink back-flow on actuation	♦ Silverbrook, EP 0771 658 A2 and related patent applications ♦ Valve-jet ♦ Tone-jet ♦ IJ08, IJ13, IJ15, IJ17. ♦ IJ18, IJ19, IJ21

Nozzle Clearing Method**[0055]**

Nozzle Clearing method	Description	Advantages	Disadvantages	Examples
Normal nozzle firing	All of the nozzles are fired periodically, before the ink has a chance to dry. When not in use the nozzles are sealed (capped) against air. The nozzle firing is usually performed during a special clearing cycle, after first moving the print head to a cleaning station.	♦ No added complexity on the print head	♦ May not be sufficient to displace dried ink	♦ Most ink jet systems ♦ IJ01- IJ07, IJ09- IJ12 ♦ IJ14, IJ16, IJ20, IJ22 ♦ IJ23- IJ34, IJ36- IJ45
Extra power to ink heater	In systems which heat the ink, but do not boil it under normal situations, nozzle clearing can be achieved by over-powering the heater and boiling ink at the nozzle.	♦ Can be highly effective if the heater is adjacent to the nozzle	♦ Requires higher drive voltage for clearing ♦ May require larger drive transistors	♦ Silverbrook, EP 0771 658 A2 and related patent applications

(continued)

Nozzle Clearing method	Description	Advantages	Disadvantages	Examples
Rapid succession of actuator pulses	The actuator is fired in rapid succession. In some configurations, this may cause heat build-up at the nozzle which boils the ink, clearing the nozzle. In other situations, it may cause sufficient vibrations to dislodge clogged nozzles.	◆ Does not require extra drive circuits on the print head ◆ Can be readily controlled and initiated by digital logic	◆ Effectiveness depends substantially upon the configuration of the inkjet nozzle	◆ May be used with: ◆ IJ01-IJ07, IJ09-IJ11 ◆ IJ14, IJ16, IJ20, IJ22 ◆ IJ23-IJ25, IJ27-IJ34 ◆ IJ36-IJ45
Extra power to ink pushing actuator	Where an actuator is not normally driven to the limit of its motion, nozzle clearing may be assisted by providing an enhanced drive signal to the actuator.	◆ A simple solution where applicable	◆ Not suitable where there is a hard limit to actuator movement	◆ May be used with: ◆ IJ03, IJ09, IJ16, IJ20 ◆ IJ23, IJ24, IJ25, U27 ◆ IJ29, IJ30, IJ31, IJ32 ◆ IJ39, IJ40, IJ41, IJ42 ◆ IJ43, IJ44, IJ45
Acoustic resonance	An ultrasonic wave is applied to the ink chamber. This wave is of an appropriate amplitude and frequency to cause sufficient force at the nozzle to clear blockages. This is easiest to achieve if the ultrasonic wave is at a resonant frequency of the ink cavity.	◆ A high nozzle clearing capability can be achieved ◆ May be implemented at very low cost in systems which already include acoustic actuators	◆ High implementation cost if system does not already include an acoustic actuator	◆ IJ08, IJ13, IJ15, IJ17 ◆ IJ18, IJ19, IJ21
Nozzle clearing plate	A microfabricated plate is pushed against the nozzles. The plate has a post for every nozzle. The array of posts	◆ Can clear severely clogged nozzles	◆ Accurate mechanical alignment is required ◆ Moving parts are required ◆ There is risk of damage to the nozzles ◆ Accurate fabrication is required	◆ Silverbrook, EP 0771 658 A2 and related patent applications

(continued)

Nozzle Clearing method	Description	Advantages	Disadvantages	Examples
Ink pressure pulse	The pressure of the ink is temporarily increased so that ink streams from all of the nozzles. This may be used in conjunction with actuator energizing.	♦ May be effective where other methods cannot be used	♦ Requires pressure pump or other pressure actuator ♦ Expensive ♦ Wasteful of ink	♦ May be used with all IJ series ink jets
Print head wiper	A flexible 'blade' is wiped across the print head surface. The blade is usually fabricated from a flexible polymer, e.g. rubber or synthetic elastomer.	♦ Effective for planar print head surfaces ♦ Low cost	♦ Difficult to use if print head surface is non-planar or very fragile ♦ Requires mechanical parts ♦ Blade can wear out in high volume print systems	♦ Many ink jet systems
Separate ink boiling heater	A separate heater is provided at the nozzle although the normal drop ejection mechanism does not require it. The heaters do not require individual drive circuits, as many nozzles can be cleared simultaneously, and no imaging is required.	♦ Can be effective where other nozzle clearing methods cannot be used ♦ Can be implemented at no additional cost in some inkjet configurations	♦ Fabrication complexity	♦ Can be used with many IJ series ink jets

Nozzle plate construction

[0056]

Nozzle plate construction	Description	Advantages	Disadvantages	Examples
Electroformed nickel	A nozzle plate is separately fabricated from electroformed nickel, and bonded to the print head chip.	♦ Fabrication simplicity	♦ High temperatures and pressures are required to bond nozzle plate ♦ Minimum thickness constraints ♦ Differential thermal expansion	♦ Hewlett Packard Thermal inkjet

(continued)

Nozzle plate construction	Description	Advantages	Disadvantages	Examples
Laser ablated or drilled polymer	Individual nozzle holes are ablated by an intense UV laser in a nozzle plate, which is typically a polymer such as polyimide or polysulphone	◆ No masks required ◆ Can be quite fast ◆ Some control over nozzle profile is possible ◆ Equipment required is relatively low cost	◆ Each hole must be individually formed ◆ Special equipment required ◆ Slow where there are many thousands of nozzles per print head ◆ May produce thin burrs at exit holes	◆ Canon Bubblejet ◆ 1988 Sercel et al., SPIE, Vol. 998 Excimer Beam Applications, pp. 76-83 ◆ 1993 Watanabe et al., USP 5,208,604
Silicon micro-machined	A separate nozzle plate is micromachined from single crystal silicon, and bonded to the print head wafer.	◆ High accuracy is attainable	◆ Two part construction ◆ High cost ◆ Requires precision alignment ◆ Nozzles may be clogged by adhesive	◆ K. Bean, IEEE Transactions on Electron Devices, Vol. ED-25, No. 10, 1978, pp 1185-1195 ◆ Xerox 1990 Hawkins et al., USP 4,899,181
Glass capillaries	Fine glass capillaries are drawn from glass tubing. This method has been used for making individual nozzles, but is difficult to use for bulk manufacturing of print heads with thousands of nozzles.	◆ No expensive equipment required ◆ Simple to make single nozzles	◆ Very small nozzle sizes are difficult to form ◆ Not suited for mass production	◆ 1970 Zoltan USP 3,683,212

(continued)

Nozzle plate construction	Description	Advantages	Disadvantages	Examples
Monolithic, surface micro-machined using VLSI lithographic processes	The nozzle plate is deposited as a layer using standard VLSI deposition techniques. Nozzles are etched in the nozzle plate using VLSI lithography and etching.	◆ High accuracy (<1 μm) ◆ Monolithic ◆ Low cost ◆ Existing processes can be used	◆ Requires sacrificial layer under the nozzle plate to form the nozzle chamber ◆ Surface may be fragile to the touch	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ IJ01, IJ02, U04, IJ11 ◆ IJ12, IJ17, IJ18, IJ20 ◆ IJ22, IJ24, IJ27, IJ28 ◆ IJ29, IJ30, IJ31, U32 ◆ IJ33, IJ34, IJ36, IJ37 ◆ IJ38, IJ39, IJ40, IJ41 ◆ IJ42, IJ43, IJ44
Monolithic, etched through substrate	The nozzle plate is a buried etch stop in the wafer. Nozzle chambers are etched in the front of the wafer, and the wafer is thinned from the back side. Nozzles are then etched in the etch stop layer.	◆ High accuracy (<1 μm) ◆ Monolithic ◆ Low cost ◆ No differential expansion	◆ Requires long etch times ◆ Requires a support wafer	◆ IJ03, IJ05, IJ06, IJ07 ◆ IJ08, IJ09, IJ10, IJ13 ◆ IJ14, IJ15, IJ16, IJ19 ◆ IJ21, IJ23, IJ25, IJ26
No nozzle plate	Various methods have been tried to eliminate the nozzles entirely, to prevent nozzle clogging. These include thermal bubble mechanisms and acoustic lens mechanisms	◆ No nozzles to become clogged	◆ Difficult to control drop position accurately ◆ Crosstalk problems	◆ Ricoh 1995 Sekiya et al USP 5,412,413 ◆ 1993 Hadimioglu et al EUP 550,192 ◆ 1993 Elrod et al EUP 572,220
Trough	Each drop ejector has a trough through which a paddle moves. There is no nozzle plate.	◆ Reduced manufacturing complexity ◆ Monolithic	◆ Drop firing direction is sensitive to wicking.	◆ IJ35

(continued)

Nozzle plate construction	Description	Advantages	Disadvantages	Examples
Nozzle slit instead of individual nozzles	The elimination of nozzle holes and replacement by a slit encompassing many actuator positions reduces nozzle clogging, but increases crosstalk due to ink surface waves	◆ No nozzles to become clogged	◆ Difficult to control drop position accurately ◆ Crosstalk problems	◆ 1989 Saito et al USP 4,799,068

Drop ejection direction**[0057]**

Ejection direction	Description	Advantages	Disadvantages	Examples
Edge ('edge shooter')	Ink flow is along the surface of the chip, and ink drops are ejected from the chip edge.	◆ Simple construction ◆ No silicon etching required ◆ Good heat sinking via substrate ◆ Mechanically strong ◆ Ease of chip handling	◆ Nozzles limited to edge ◆ High resolution is difficult ◆ Fast color printing requires one print head per color	◆ Canon Bubblejet 1979 Endo et al GB patent 2,007,162 ◆ Xerox heater-in-pit 1990 Hawkins et al USP 4,899,181 ◆ Tone-jet
Surface ('roof shooter')	Ink flow is along the surface of the chip, and ink drops are ejected from the chip surface, normal to the plane of the chip.	◆ No bulk silicon etching required ◆ Silicon can make an effective heat sink ◆ Mechanical strength	◆ Maximum ink flow is severely restricted	◆ Hewlett-Packard TIJ 1982 Vaught et al USP 4,490,728 ◆ IJ02, IJ11, IJ12, IJ20 ◆ IJ22
Through chip, forward ('up shooter')	Ink flow is through the chip, and ink drops are ejected from the front surface of the chip.	◆ High ink flow ◆ Suitable for pagewidth print ◆ High nozzle packing density therefore low manufacturing cost	◆ Requires bulk silicon etching	◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ IJ04, IJ17, IJ18, IJ24 ◆ IJ27-IJ45

(continued)

Ejection direction	Description	Advantages	Disadvantages	Examples
Through chip, reverse ('down shooter')	Ink flow is through the chip, and ink drops are ejected from the rear surface of the chip.	◆ High ink flow ◆ Suitable for pagewidth print ◆ High nozzle packing density therefore low manufacturing cost	◆ Requires wafer thinning ◆ Requires special handling during manufacture	◆ IJ01, IJ03, IJ05, IJ06 ◆ IJ07, IJ08, IJ09, IJ10 ◆ IJ13, IJ14, IJ15, IJ16 ◆ IJ19, IJ21, IJ23, IJ25 ◆ IJ26
Through actuator	Ink flow is through the actuator, which is not fabricated as part of the same substrate as the drive transistors.	◆ Suitable for piezoelectric print heads	◆ Pagewidth print heads require several thousand connections to drive circuits ◆ Cannot be manufactured in standard CMOS fabs ◆ Complex assembly required	◆ Epson Stylus ◆ Tektronix hot melt piezoelectric ink jets

Ink type**[0058]**

Ink type	Description	Advantages	Disadvantages	Examples
Aqueous, dye	Water based ink which typically contains: water, dye, surfactant, humectant, and biocide. Modern ink dyes have high water-fastness, light fastness	◆ Environmentally friendly ◆ No odor	◆ Slow drying ◆ Corrosive ◆ Bleeds on paper ◆ May strikethrough ◆ Cockles paper	◆ Most existing inkjets ◆ All U series ink jets ◆ Silverbrook, EP 0771 658 A2 and related patent applications
Aqueous, pigment	Water based ink which typically contains: water, pigment, surfactant, humectant, and biocide. Pigments have an advantage in reduced bleed, wicking and strikethrough.	◆ Environmentally friendly ◆ No odor ◆ Reduced bleed ◆ Reduced wicking ◆ Reduced strikethrough	◆ Slow drying ◆ Corrosive ◆ Pigment may clog nozzles ◆ Pigment may clog actuator mechanisms ◆ Cockles paper	◆ IJ02, IJ04, IJ21, IJ26 ◆ IJ27, IJ30 ◆ Silverbrook, EP 0771 658 A2 and related patent applications ◆ Piezoelectric ink-jets ◆ Thermal ink jets (with significant restrictions)

(continued)

Ink type	Description	Advantages	Disadvantages	Examples
Methyl Ethyl Ketone (MEK)	MEK is a highly volatile solvent used for industrial printing on difficult surfaces such as aluminum cans.	♦ Very fast drying ♦ Prints on various substrates such as metals and plastics	♦ Odorous ♦ Flammable	♦ All IJ series ink jets
Alcohol (ethanol, 2-butanol, and others)	Alcohol based inks can be used where the printer must operate at temperatures below the freezing point of water. An example of this is in-camera consumer photographic printing.	♦ Fast drying ♦ Operates at sub-freezing temperatures ♦ Reduced paper cockle ♦ Low cost	♦ Slight odor ♦ Flammable	♦ All IJ series ink jets
Phase change (hot melt)	The ink is solid at room temperature, and is melted in the print head before jetting. Hot melt inks are usually wax based, with a melting point around 80 °C. After jetting the ink freezes almost instantly upon contacting the print medium or a transfer roller.	♦ No drying time-ink instantly freezes on the print medium ♦ Almost any print medium can be used ♦ No paper cockle occurs ♦ No wicking occurs ♦ No bleed occurs ♦ No strikethrough occurs	♦ High viscosity ♦ Printed ink typically has a 'waxy' feel ♦ Printed pages may 'block' ♦ Ink temperature may be above the curie point of permanent magnets ♦ Ink heaters consume power ♦ Long warm-up time	♦ Tektronix hot melt piezoelectric ink jets ♦ 1989 Nowak USP 4,820,346 ♦ All IJ series ink jets
Oil	Oil based inks are extensively used in offset printing. They have advantages in improved characteristics on paper (especially no wicking or cockle). Oil soluble dyes and pigments are required.	♦ High solubility medium for some dyes ♦ Does not cockle paper ♦ Does not wick through paper	♦ High viscosity: this is a significant limitation for use in inkjets, which usually require a low viscosity. Some short chain and multi-branched oils have a sufficiently low viscosity. ♦ Slow drying	♦ All IJ series ink jets

Ink Jet Printing

[0059] A large number of new forms of ink jet printers have been developed to facilitate alternative ink jet technologies for the image processing and data distribution system. Various combinations of ink jet devices can be included in printer devices incorporated as part of the present invention.

Ink Jet Manufacturing

[0060] Further, the present application may utilize advanced semiconductor fabrication techniques in the construction of large arrays of ink jet printers.

Fluid Supply

[0061] Further, the present application may utilize an ink delivery system to the ink jet head.

MEMS Technology

[0062] Further, the present application may utilize advanced semiconductor microelectromechanical techniques in the construction of large arrays of ink jet printers.

IR Technologies

[0063] Further, the present application may include the utilization of a disposable camera system.

DotCard Technologies

[0064] Further, the present application may include the utilization of a data distribution system.

Artcam Technologies

[0065] Further, the present application may include the utilization of camera and data processing techniques such as an Artcam type device.

[0066] It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiment without departing from the scope of the invention as broadly described. The present embodiment is, therefore, to be considered in all respects to be illustrative and not restrictive.

Claims

1. An ink jet nozzle arrangement (4401) for the ejection of ink from an ink ejection nozzle comprising:

a substrate (4413);
a conductive coil (4410) operable in a controlled manner;
a moveable magnetic actuator forming an ink nozzle chamber (4402) between said substrate (4413) and said actuator (4405), said moveable magnetic actuator further including an ink ejection nozzle (4403) defined therein;
wherein variations in the energization level of said conductive coil (4410) cause said magnetic actuator (4405) to move from a first position to a second position, thereby causing a consequential ejection of ink from said nozzle chamber (4402) as a result of fluctuations in the ink pressure within said nozzle chamber,

characterized in that:

said conductive coil (4410) is formed on said substrate (4413); and
said moveable magnetic actuator (4405) surrounds said conductive coil (4410).

2. An inkjet nozzle arrangement (4401) as claimed in claim 1 further comprising an ink supply channel (4412) inter-connecting said nozzle chamber (4402) for the resupply of ink to said nozzle chamber.

3. An inkjet nozzle arrangement (4401) as claimed in any of claims 1 or 2 wherein said moveable magnetic actuator (4405) is moveable from a first position having an expanded nozzle chamber volume to a second position having a contracted nozzle chamber volume by the operation of said conductive coil (4410).

4. An inkjet nozzle arrangement (4401) as claimed in claim 3 further comprising:

at least one resilient member (4406) attached to said moveable magnetic actuator (4405), so as to bias said moveable magnetic actuator, in its quiescent position, at said first position.

- 5 5. An ink jet nozzle arrangement (4401) as claimed in claim 4 wherein said at least one resilient member (4406) comprises a leaf spring.
6. An ink jet nozzle (4401) arrangement as claimed in claim 2 wherein said interconnection comprises a series of elongated slots (4414) etched in said substrate.
- 10 7. An inkjet nozzle arrangement (4401) as claimed in claim 1 wherein said substrate (4413) comprises a silicon wafer and said ink supply channel (4412) is etched through said wafer.
8. An ink jet nozzle arrangement (4401) as claimed in any of claims 1 to 7 wherein a slot is defined between said magnetic actuator (4405) and said substrate (4413) and the actuator portions adjacent said slot is hydrophobically treated so as to minimize wicking through said slot.
- 15 9. An ink jet nozzle arrangement (4401) as claimed in any of claims 1 to 8 further comprising a magnetic base plate (4409) located between said conductive coil (4410) and said substrate (4413).
- 20 10. An ink jet nozzle arrangement (4401) as claimed in claim 9 wherein said magnetic actuator (4405) and said base plate (4409) substantially encompasses said conductive coil (4410).

Patentansprüche

- 25 1. Tintenstrahl-Düsenanordnung (4401) zum Ausstoßen von Tinte aus einer Tintenausstoßdüse, umfassend:

ein Substrat (4413);
 eine leitende Spule (4410), die gesteuert betrieben werden kann;
 30 ein bewegliches magnetisches Stellorgan, das eine Tintendüsenkammer (4402) zwischen dem Substrat (4413) und dem Stellorgan (4405) bildet, wobei das bewegliche magnetische Stellorgan darüber hinaus eine darin gebildete Tintenausstoßdüse (4403) umfasst; wobei Veränderungen des Stromversorgungsgrads der leitenden Spule (4410) das bewegliche Stellorgan (4405) sich von einer ersten Position in eine zweite Position bewegen lassen, wodurch ein daraus folgendes Ausstoßen von Tinte aus der Düsenkammer (4402) als Ergebnis von
 35 Schwankungen des Tintendrucks in der Düsenkammer herbeigeführt wird,

dadurch gekennzeichnet, dass:

die leitende Spule (4410) auf dem Substrat (4413) gebildet ist; und
 40 das bewegliche magnetische Stellorgan (4405) die leitende Spule (4410) umgibt.

2. Tintenstrahl-Düsenanordnung (4401) nach Anspruch 1, darüber hinaus einen Tintenzufuhrkanal (4412) umfassend, der mit der Düsenkammer (4402) verbunden ist, um diese wieder mit Tinte zu füllen.
- 45 3. Tintenstrahl-Düsenanordnung (4401) nach einem der Ansprüche 1 oder 2, wobei das bewegliche magnetische Stellorgan (4405) durch den Betrieb der leitenden Spule (4410) aus einer ersten Position mit einem vergrößerten Düsenkammervolumen in eine zweite Position bewegbar ist, die ein geschrumpftes Düsenkammervolumen hat.
4. Tintenstrahl-Düsenanordnung (4401) nach Anspruch 3, darüber hinaus umfassend:
- 50 wenigstens ein am beweglichen magnetischen Stellorgan (4405) angebrachtes elastisches Element (4406), um das bewegliche magnetische Stellorgan in seiner Ruheposition an der ersten Position vorzuspannen.
5. Tintenstrahl-Düsenanordnung (4401) nach Anspruch 4, wobei das wenigstens eine elastische Element (4406) eine Blattfeder umfasst.
- 55 6. Tintenstrahl-Düsenanordnung (4401) nach Anspruch 2, wobei die Verbindung eine Reihe von Längsschlitzen (4414) umfasst, die in das Substrat eingeätzt sind.

7. Tintenstrahl-Düsenanordnung (4401) nach Anspruch 1, wobei das Substrat (4413) einen Siliziumwafer umfasst und ein Tintenzufuhrkanal (4412) durch den Wafer geätzt ist.
8. Tintenstrahl-Düsenanordnung (4401) nach einem der Ansprüche 1 bis 7, wobei zwischen dem magnetischen Stellorgan (4405) und dem Substrat (4413) ein Schlitz definiert ist, und die an den Schlitz angrenzenden Stellorganabschnitte hydrophob behandelt sind, um eine Dochtwirkung durch den Schlitz zu minimieren.
9. Tintenstrahl-Düsenanordnung (4401) nach einem der Ansprüche 1 bis 8, darüber hinaus eine magnetische Grundplatte (4409) umfassend, die zwischen der leitenden Spule (4410) und dem Substrat (4413) sitzt.
10. Tintenstrahl-Düsenanordnung (4401) nach Anspruch 9, wobei das magnetische Stellorgan (4405) und die Grundplatte (4409) die leitende Spule (4410) im Wesentlichen umgeben.

Revendications

1. Agencement de buse de jet d'encre (4401) pour l'éjection d'encre depuis une buse de jet d'encre comprenant:

un substrat (4413) ;
 une bobine conductrice (4410) pouvant fonctionner d'une manière commandée ;
 un actionneur magnétique mobile formant une chambre de buse d'encre (4402) entre ledit substrat (4413) et ledit actionneur (4405), ledit actionneur magnétique mobile comprenant en outre une buse d'éjection d'encre (4403) définie dans celui-ci ; dans lequel des variations dans le niveau d'excitation de ladite bobine conductrice (4410) provoquent un mouvement dudit actionneur magnétique (4405) d'une première position vers une deuxième position, provoquant ainsi une éjection en conséquence d'encre depuis la chambre de buse (4402) comme résultat de fluctuation dans la pression d'encre à l'intérieur de la chambre de buse,

caractérisé en ce que :

ladite bobine conductrice (4410) est formée sur ledit substrat (4413) ;
 ledit actionneur magnétique mobile (4405) entoure ladite bobine conductrice (4410).

2. Agencement de buse de jet d'encre (4401) comme revendiqué dans la revendication 1 comprenant en outre un canal de fourniture d'encre (4412) interconnectant à ladite chambre de buse (4402) pour fournir à nouveau de l'encre à ladite chambre de buse.
3. Agencement de buse de jet d'encre (4401) comme revendiqué dans l'une quelconque des revendications 1 ou 2 dans lequel ledit actionneur magnétique mobile (4405) est mobile d'une première position ayant un volume de chambre de buse expansé vers une deuxième position ayant un volume de chambre de buse contracté, par l'opération de ladite bobine conductrice (4410).
4. Agencement de buse de jet d'encre (4401) comme revendiqué dans la revendication 3 comprenant en outre :
 au moins un élément élastique (4406) fixé audit actionneur magnétique mobile (4405), de manière à biaiser ledit actionneur magnétique mobile, dans sa position de repos, à ladite première position.
5. Agencement de buse de jet d'encre (4401) comme revendiqué dans la revendication 4 dans lequel au moins un élément élastique (4406) comporte un ressort à lames.
6. Agencement de buse de jet d'encre (4401) comme revendiqué dans la revendication 2 dans lequel ladite interconnexion comprend une série de fentes allongées (4414) gravées dans ledit substrat.
7. Agencement de buse de jet d'encre (4401) comme revendiqué dans la revendication 1 dans lequel ledit substrat (4413) comporte une galette de silicium et ledit canal de fourniture d'encre (4412) est gravé à travers ladite galette.
8. Agencement de buse de jet d'encre (4401) comme revendiqué dans l'une quelconque des revendications 1 à 7 dans laquelle une fente est définie entre ledit actionneur magnétique (4405) et ledit substrat (4413) et les parties de l'actionneur à proximité de ladite fente sont traitées de manière hydrophobe de manière à minimiser les effets

de mèche à travers ladite fente.

5 9. Agencement de buse de jet d'encre (4401) comme revendiqué dans l'une quelconque des revendication 1 à 8 comprenant en outre une plaque de base magnétique (4409) située entre ladite bobine conductrice (4410) et ledit substrat (4413).

10 10. Agencement de buse de jet d'encre (4401) comme revendiqué dans la revendication 9 dans laquelle ledit actionneur magnétique (4405) et lesdites plaques de base (4409) enclavent sensiblement ladite bobine conductrice (4410)

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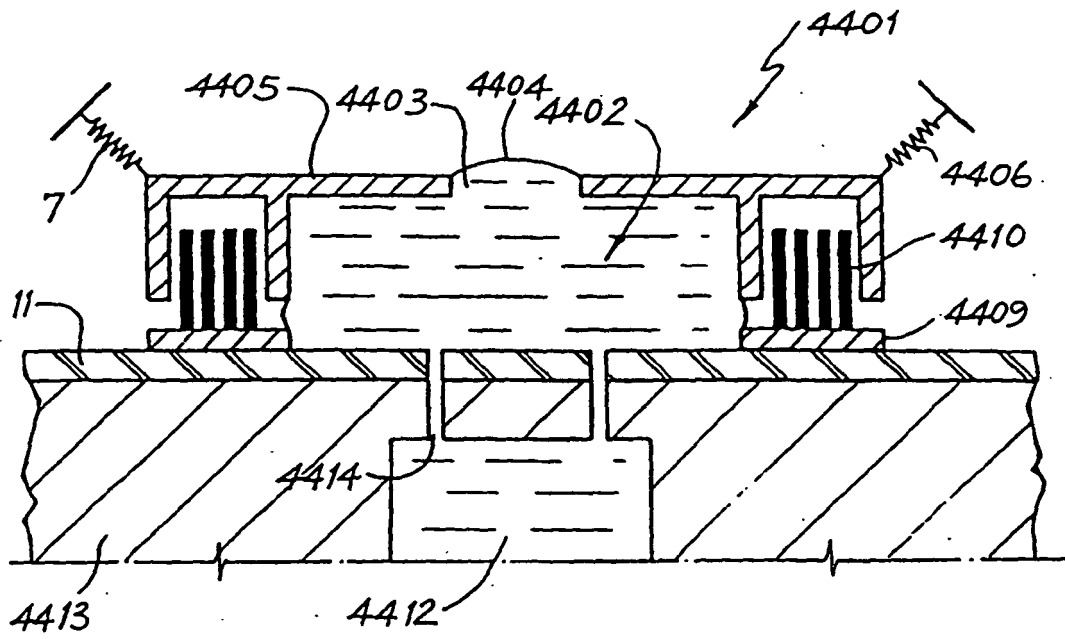


FIG. 327

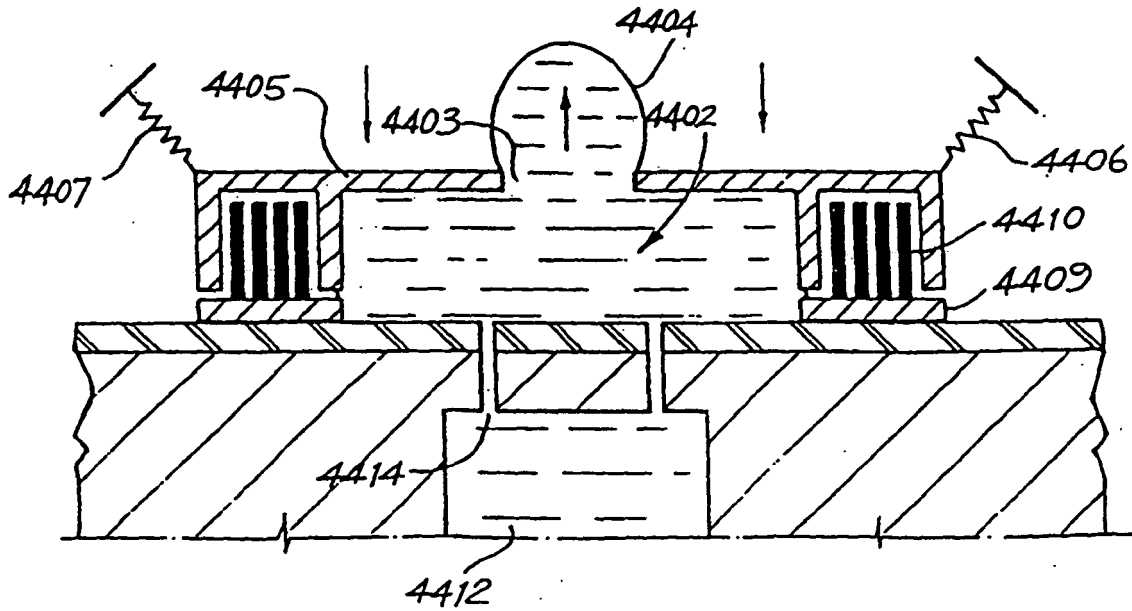


FIG. 328

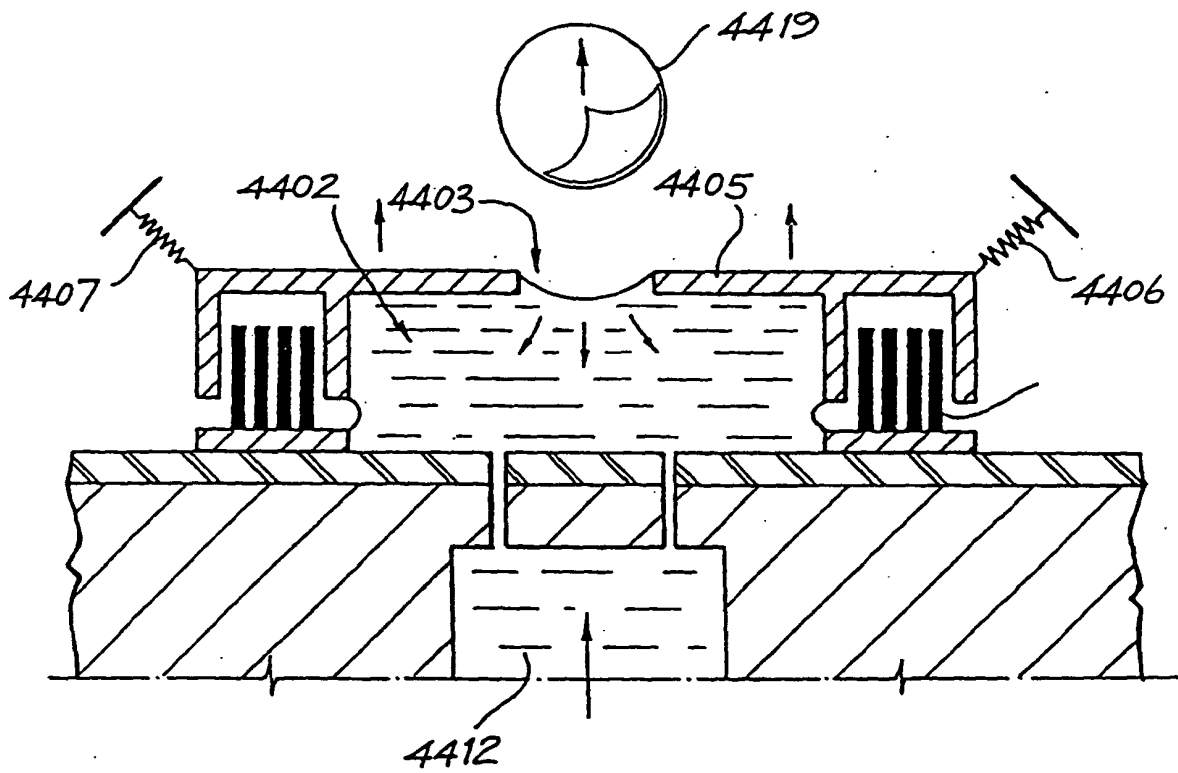


FIG. 329

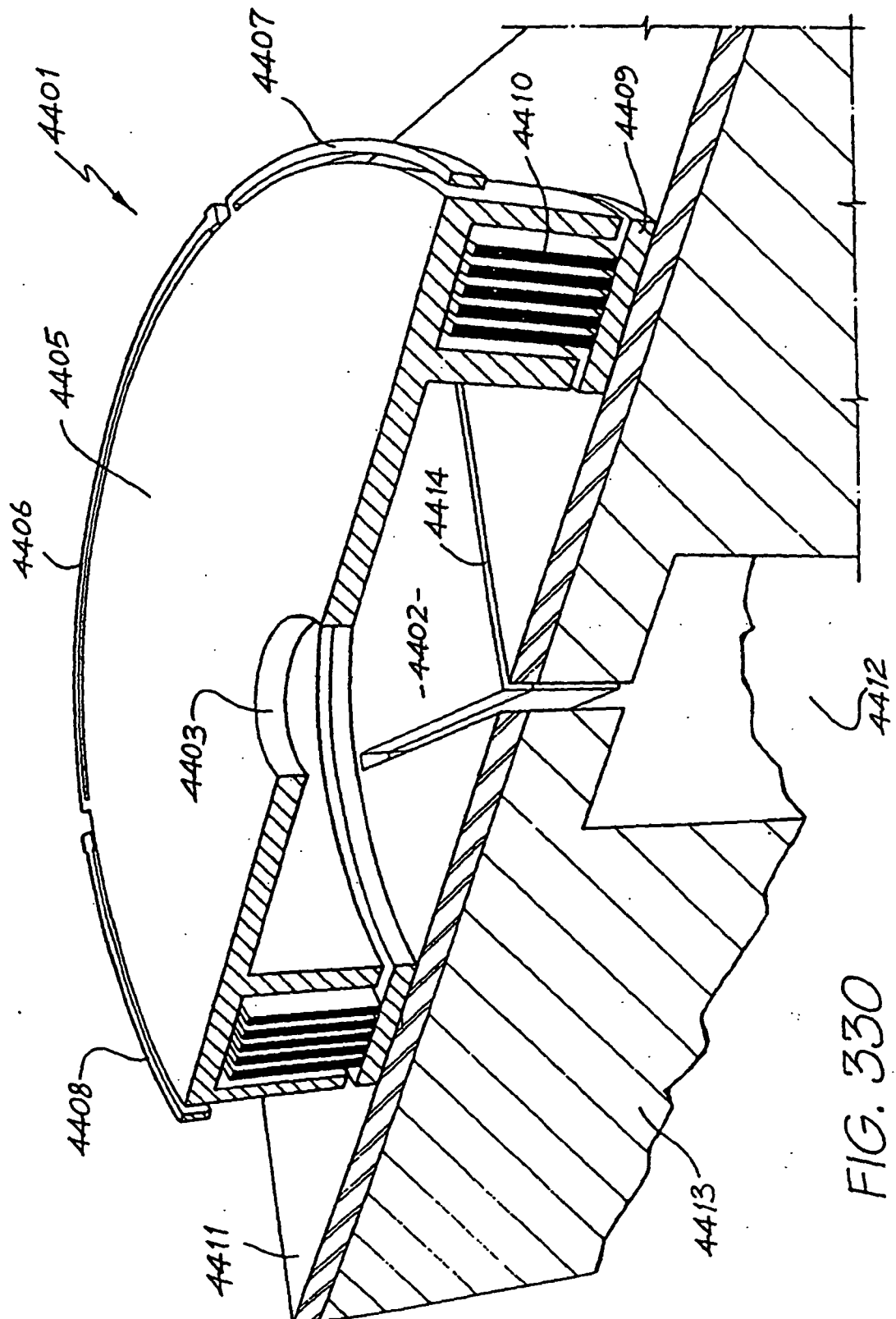


FIG. 330

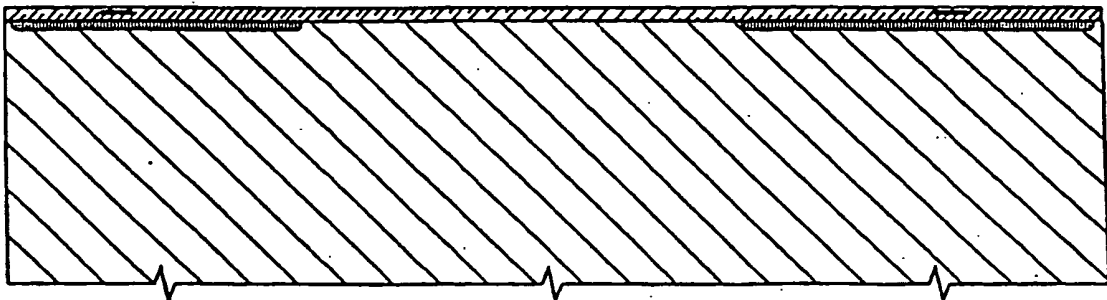
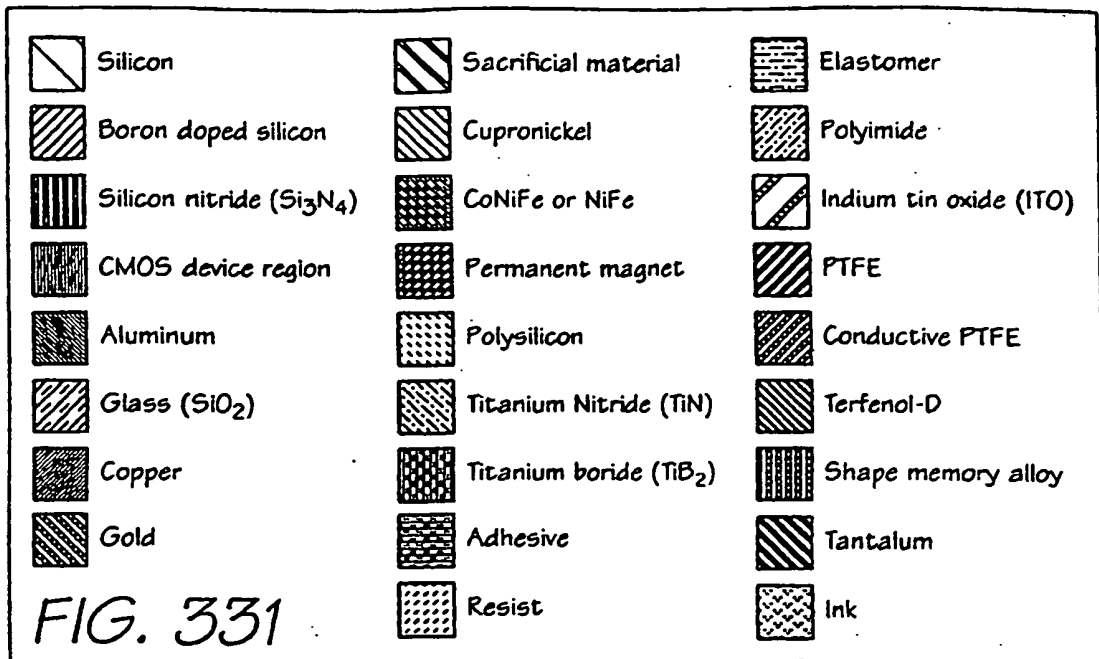


FIG. 332

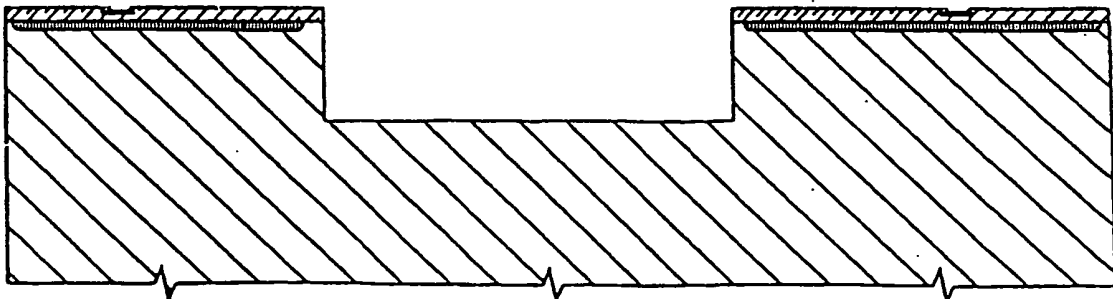


FIG. 333

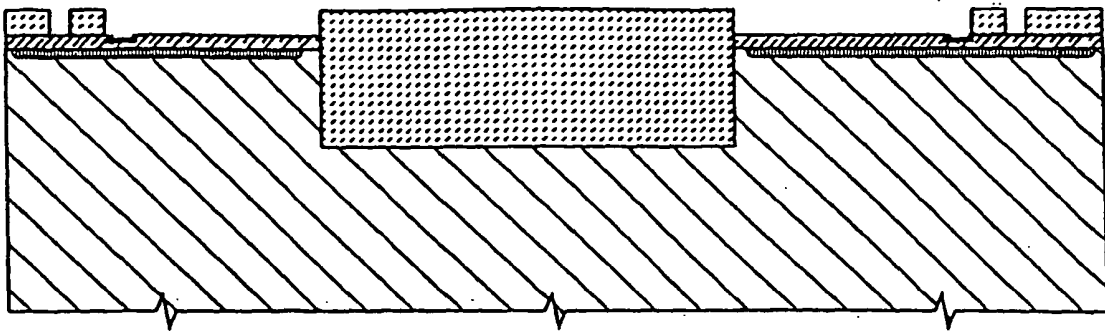


FIG. 334

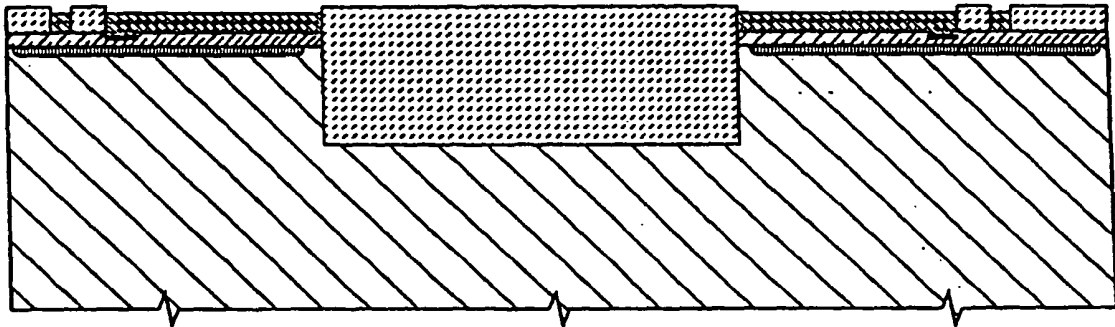


FIG. 335

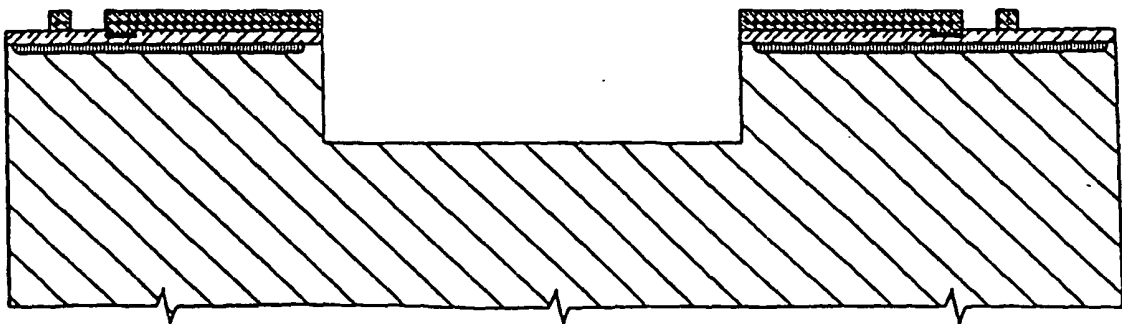


FIG. 336

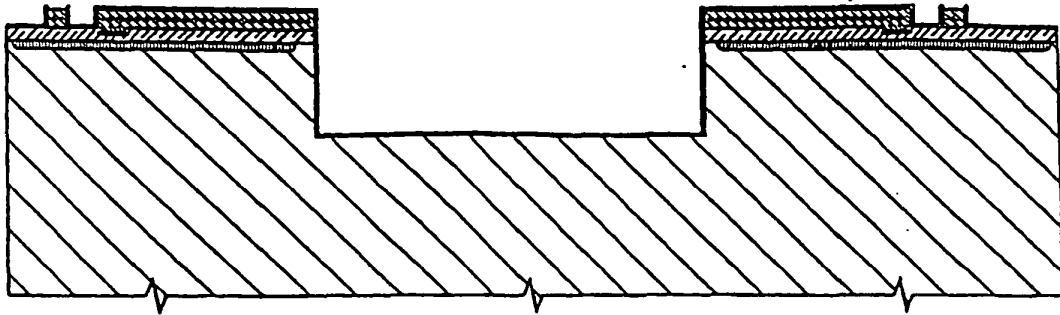


FIG. 337

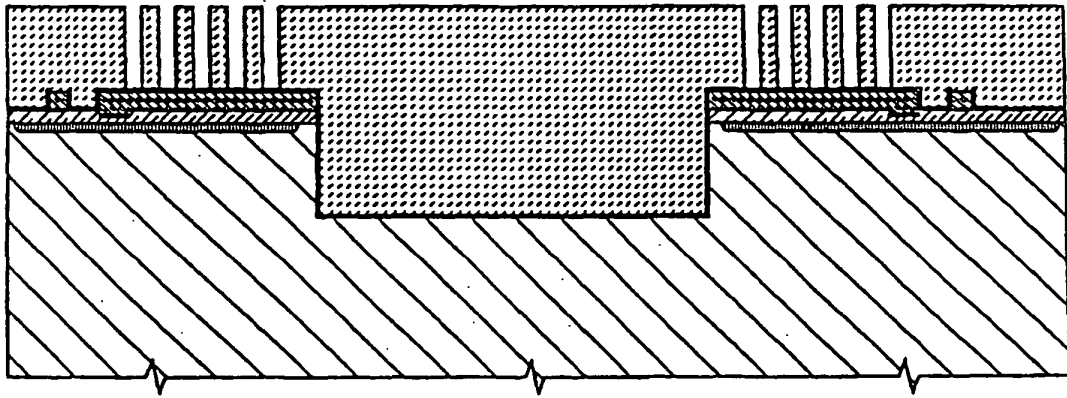


FIG. 338

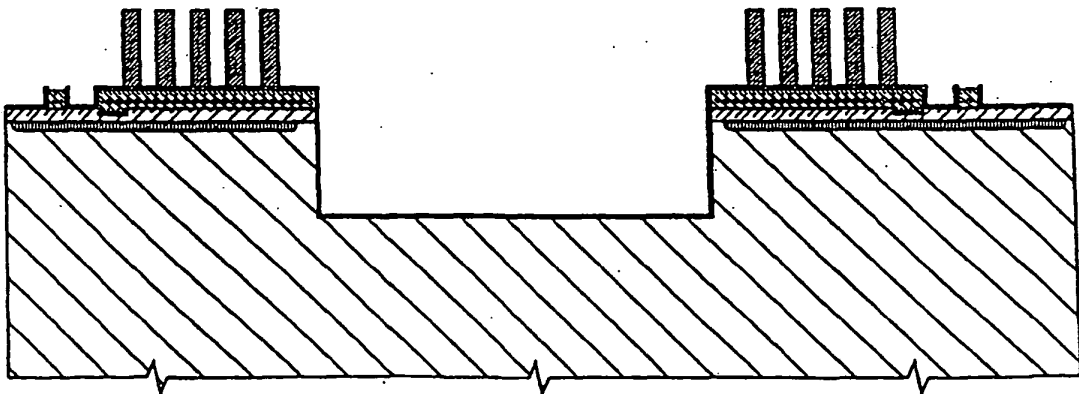


FIG. 339

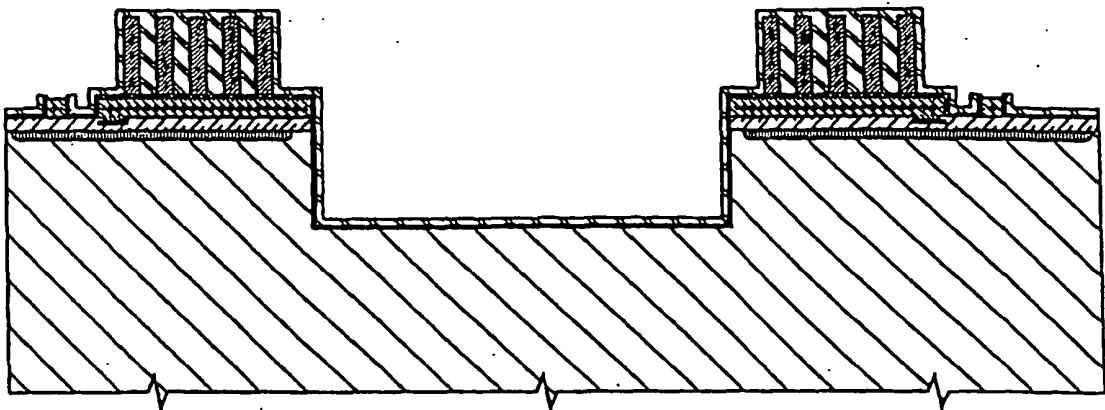


FIG. 340

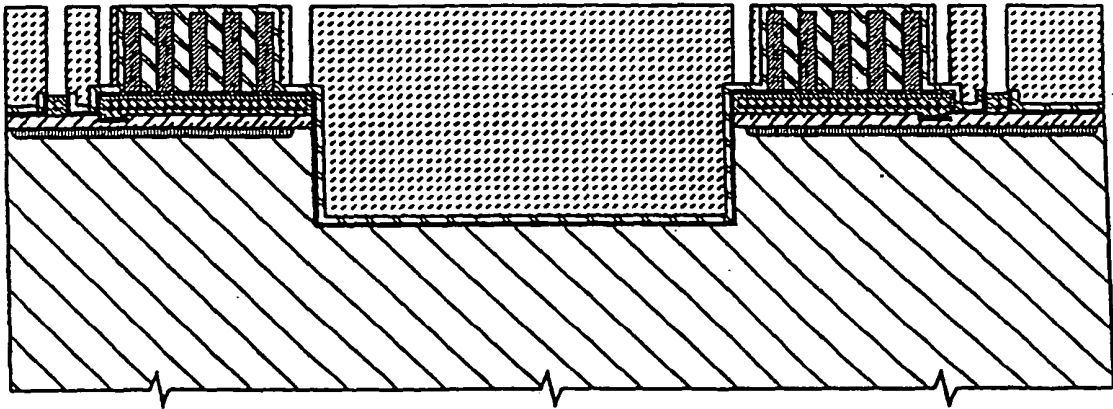


FIG. 341

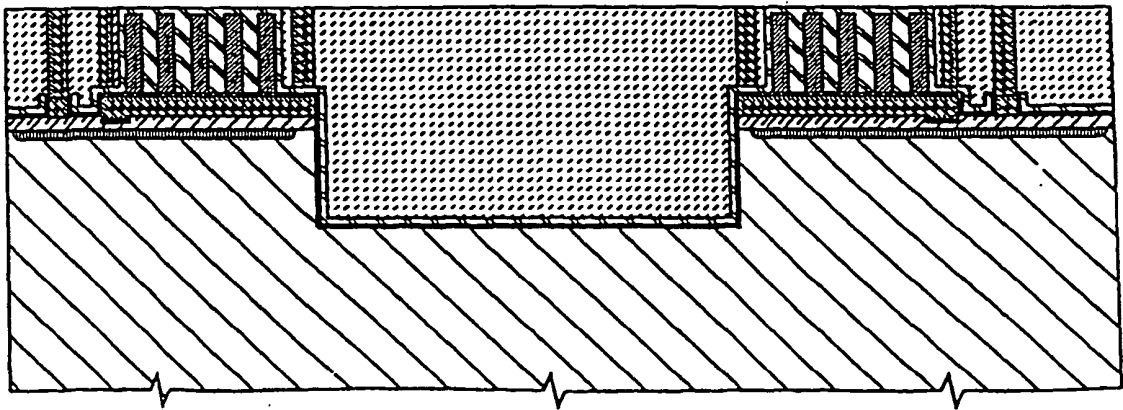


FIG. 342

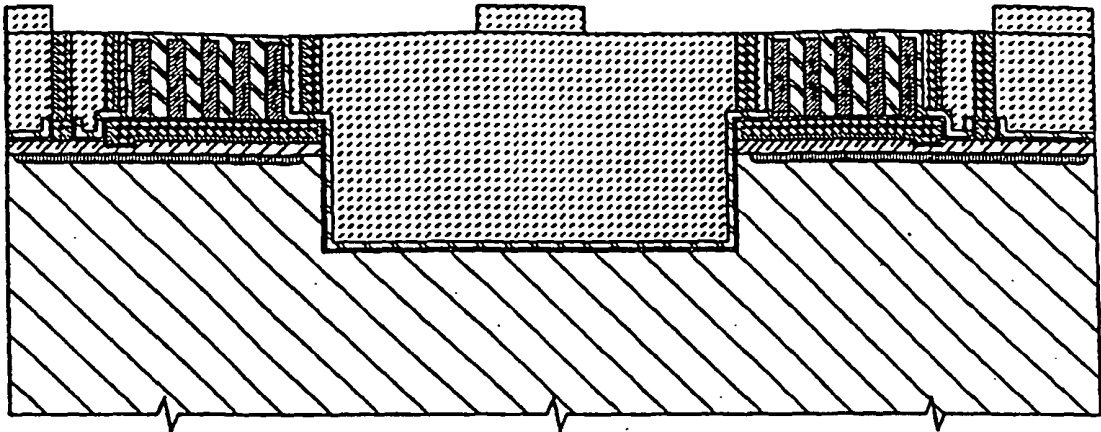


FIG. 343

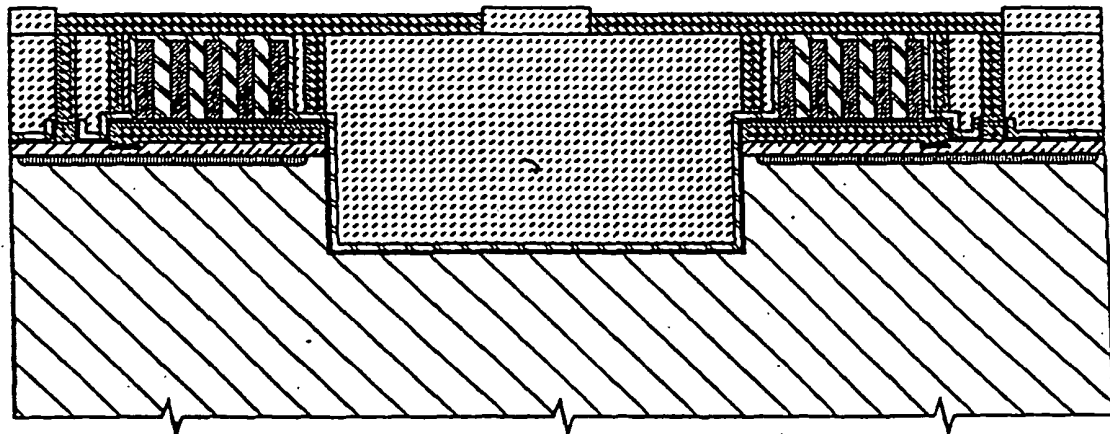


FIG. 344

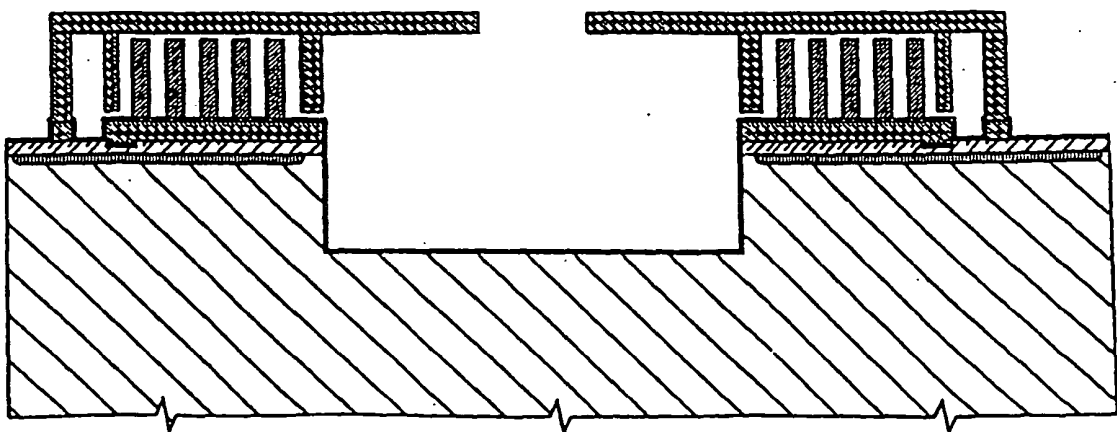


FIG. 345

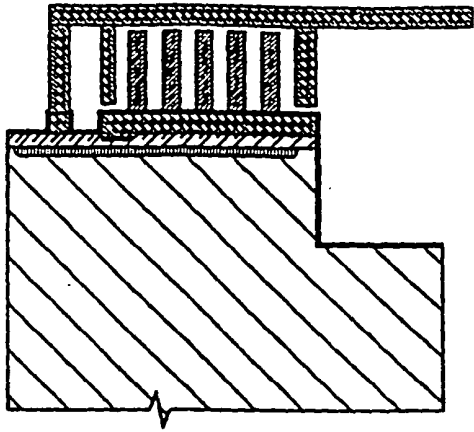


FIG. 346

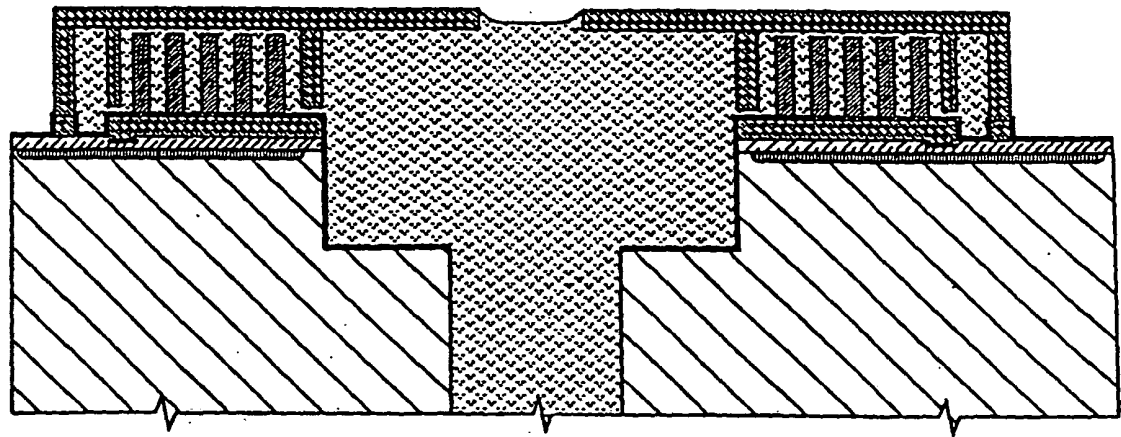
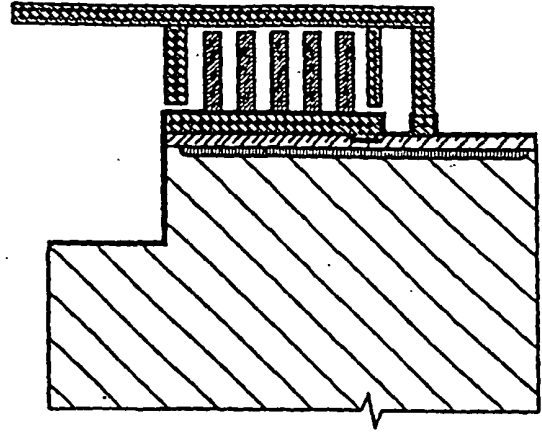


FIG. 347