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(54) **Inkjet nozzle with electromagnetic shutter**

Tintenstrahldüse mit elektromagnetischem Verschluss

buse à jet d'encre avec obturateur électromagnétique

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Description

Field of Invention

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

Background of the Art

[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.

[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).

[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 Elmjet and Scitex (see also US Patent No. 3373437 by Sweet et al)

[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.

[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.

[0009] US 4,723,131 describes a printhead comprising a plurality of nozzles and a membrane providing a flexible closure between an ink supply and each nozzle. The membrane may be actuated by a solenoid to allow ink to flow to a nozzle

[0010] GB 2262152 describes a solenoid valve for an inkjet nozzle. A plunger reciprocates inside a bore and can be electromagnetically actuated to provide a closure over an outlet to a nozzle.

[0011] US 4,210,920 discloses an ink jet printer with an ink reservoir that is held under fluctuating pressure. Drops are ejected through nozzle chambers. A catcher is provided between nozzles and media, attracting non-print-drops electrostatically.

[0012] 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.

[0013] Many inkjet 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.

[0014] 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.

[0015] 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.

[0016] 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.

[0017] 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

[0018] 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.

[0019] Accordingly the invention provides an ink jet nozzle according to claim 1. Advantageous embodiments are provided in the dependent claims.

Brief Description of the Drawings

[0020] 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. 112 is a perspective view of a single ink jet nozzle constructed in accordance with an embodiment, with the shutter means in its closed position;
Fig. 113 is a perspective view of a single inkjet nozzle constructed in accordance with an embodiment, with the shutter means in its open position;
Fig. 114 is an exploded perspective view illustrating the construction of a single ink jet nozzle in accordance with an embodiment;
Fig. 115 provides a legend of the materials indicated in Fig. 116 to Fig. 137; and
Fig. 116 to Fig. 137 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

[0021] The preferred embodiments and other embodiments will be discussed under separate headings with the heading including an U 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 IJ08 SF

[0022] In an embodiment, a shutter is actuated by means of a magnetic coil, the coil being utilized to move an attached shutter to thereby cause the shutter to open or close. The shutter is disposed between an ink reservoir having an oscillating ink pressure and a nozzle chamber having an ink ejection port defined therein for the ejection of ink. When the shutter is open, ink is allowed to flow from the ink reservoir through to the nozzle chamber and thereby cause an ejection of ink from the ink ejection port. When the shutter is closed, the nozzle chamber remains in a stable state such that no ink is ejected from the chamber.

[0023] Turning now to Fig. 112, there is illustrated a single inkjet nozzle arrangement 710 in a closed position. The arrangement 710 includes a series of shutters 711 which are located above corresponding apertures to a nozzle chamber. In Fig. 113, the ink jet nozzle 710 is illustrated in an open position which also illustrates the apertures 712 providing a fluid interconnection to a nozzle chamber 713 and an ink ejection port 714. The shutters e.g. 711 are interconnected together and further connected to an arm 716 which is pivotally mounted about a pivot point 717 about which the shutters e.g. 711 rotate. The shutter 711 and arm 716 are constructed from nickel iron (NiFe) so as to be magnetically attracted to an electromagnetic device 719. The electromagnetic device 719 comprises a NiFe core 720 around which is constructed a copper coil 721. The copper coil 721 is connected to a lower drive layer via vias 723,724. The coil 719 is activated by sending a current through the coil 721 which results in its magnification and corresponding attraction in the areas 726,727. The high levels of attraction are due to its close proximity to the ends of the electromagnet 719. This results in a general rotation of the surfaces 726,727 around the pivot point 717 which in turn results in a corresponding rotation of the shutter from a closed to an open position.

[0024] A number of coiled springs 730-732 are also provided. The coiled springs store energy as a consequence of the rotation of the shutter 711. Hence, upon deactivation of the electromagnet 719 the coil springs 730-732 act to return the shutter to its closed position. As mentioned previously, the opening and closing of the shutter 711 allows for the flow of ink to the ink nozzle chamber for a subsequent ejection. The coil 719 is activated rotating the arm 716 bringing the surfaces 726,727 into close contact with the electromagnet 719. The surfaces 726,727 are kept in contact with the electromagnet 719 by means of utilisation of a keeper current which, due the close proximity between the surfaces is substantially less than that required to initially move the arm 716.

[0025] The shutter 711 is maintained in the plane by means of a guide 734 which overlaps slightly with an end portion of the shutter 711.

[0026] Turning now to Fig. 114, there is illustrated an exploded perspective of one form of construction of a nozzle arrangement 710 in accordance with an embodiment. The bottom level consists of a boron doped silicon layer 740 which can be formed from constructing a buried epitaxial layer within a selected wafer and then back etching utilising the boron doped layer as an etch stop. Subsequently, there is provided a silicon layer 741 which includes a crystallographically etched pit forming the nozzle chamber 713. On top of the silicon layer 741 there is constructed a 2 micron silicon dioxide layer 742 which includes the nozzle chamber pit opening whose side walls are passivated by a subsequent nitride layer. On top of the silicon dioxide layer 742 is constructed a nitride layer 744 which provides passivation of the lower silicon dioxide layer and also provides a base on which to construct the electromagnetic portions and the shutter. The nitride layer 744 and lower silicon dioxide layer having suitable vias for the interconnection to the ends of the electromagnetic circuit for the purposes of supplying power on demand to the electromagnetic circuit

[0027] Next, a copper layer 745 is provided. The copper layer providing a base wiring layer for the electromagnetic array in addition to a lower portion of the pivot 717 and a lower portion of the copper layer being utilised to form a part of the construction of the guide 734.

[0028] Next, a NiFe layer 747 is provided which is utilized for the formation of the internal portions 720 of the electromagnet, in addition to the pivot, aperture arm and shutter 711 in addition to a portion of the guide 734, in addition to the various spiral springs. On top of the NiFe layer 747 is provided a copper layer 749 for providing the top and side windings of the coil 721 in addition to providing the formation of the top portion of guide 734. Each of the layers 745,747 can be conductively insulated from its surroundings where required through the utilisation of a nitride passivation layer (not shown). Further, a top passivation layer can be provided to cover the various top layers which will be exposed to the ink within the ink reservoir and nozzle chamber. The various levels 745,749 can be formed through the utilisation of supporting sacrificial structures which are subsequently sacrificially etched away to leave the operable device.

[0029] 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 deposit 3 microns of epitaxial silicon heavily doped with boron.
2. Deposit 10 microns of epitaxial silicon, either p-type or n-type, depending upon the CMOS process used.
3. Complete a 0.5 micron, one poly, 2 metal CMOS process. This step is shown in Fig. 116. For clarity, these diagrams may not be to scale, and may not represent a cross section though any single plane of the nozzle. Fig. 115 is a key to representations of various materials in these manufacturing diagrams, and those of other cross referenced inkjet configurations.
4. Etch the CMOS oxide layers down to silicon or aluminum using Mask 1. This mask defines the nozzle chamber, and the edges of the print heads chips. This step is shown in Fig. 117.
5. Crystallographically etch the exposed silicon using KOH. This etch stops on <111> crystallographic planes, and on the boron doped silicon buried layer. This step is shown in Fig. 118.
6. Deposit 10 microns of sacrificial material. Planarize down to oxide using CMP. The sacrificial material temporarily fills the nozzle cavity. This step is shown in Fig. 119.
7. Deposit 0.5 microns of silicon nitride (Si_3N_4).
8. Etch nitride and oxide down to aluminum or sacrificial material using Mask 3. This mask defines the contact vias from the aluminum electrodes to the solenoid, as well as the fixed grill over the nozzle cavity. This step is shown in Fig. 120.
9. Deposit a seed layer of copper. Copper is used for its low resistivity (which results in higher efficiency) and its high electromigration resistance, which increases reliability at high current densities.
10. Spin on 2 microns of resist, expose with Mask 4, and develop. This mask defines the lower side of the solenoid square helix, as well as the lowest layer of the shutter grill vertical stop. The resist acts as an electroplating mold. This step is shown in Fig. 121.
11. Electroplate 1 micron of copper. This step is shown in Fig. 122.
12. Strip the resist and etch the exposed copper seed layer. This step is shown in Fig. 123.
13. Deposit 0.1 microns of silicon nitride.
14. Deposit 0.5 microns of sacrificial material.
15. Etch the sacrificial material down to nitride using Mask 5. This mask defines the solenoid, the fixed magnetic pole, the pivot, the spring posts, and the middle layer of the shutter grill vertical stop. This step is shown in Fig. 124.

16. 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)].
17. Spin on 3 microns of resist, expose with Mask 6, and develop. This mask defines all of the soft magnetic parts, being the fixed magnetic pole, the pivot, the shutter grill, the lever arm, the spring posts, and the middle layer of the shutter grill vertical stop. The resist acts as an electroplating mold. This step is shown in Fig. 125.
18. Electroplate 2 microns of CoNiFe. This step is shown in Fig. 126.
19. Strip the resist and etch the exposed seed layer. This step is shown in Fig. 127.
20. Deposit 0.1 microns of silicon nitride (Si_3N_4).
21. Spin on 2 microns of resist, expose with Mask 7, and develop. This mask defines the solenoid vertical wire segments, for which the resist acts as an electroplating mold. This step is shown in Fig. 128.
22. Etch the nitride down to copper using the Mask 7 resist.
23. Electroplate 2 microns of copper. This step is shown in Fig. 129.
24. Deposit a seed layer of copper.
25. Spin on 2 microns of resist, expose with Mask 8, and develop. This mask defines the upper side of the solenoid square helix, as well as the upper layer of the shutter grill vertical stop. The resist acts as an electroplating mold. This step is shown in Fig. 130.
26. Electroplate 1 micron of copper. This step is shown in Fig. 131.
27. Strip the resist and etch the exposed copper seed layer, and strip the newly exposed resist. This step is shown in Fig. 132.
28. Deposit 0.1 microns of conformal silicon nitride as a corrosion barrier.
29. Open the bond pads using Mask 9.
30. Wafer probe. All electrical connections are complete at this point, bond pads are accessible, and the chips are not yet separated.
31. Mount the wafer on a glass blank and back-etch the wafer using KOH, with no mask. This etch thins the wafer and stops at the buried boron doped silicon layer. This step is shown in Fig. 133.
32. Plasma back-etch the boron doped silicon layer to a depth of 1 micron using Mask 9. This mask defines the nozzle rim. This step is shown in Fig. 134.
33. Plasma back-etch through the boron doped layer using Mask 10. This mask defines the nozzle, and the edge of the chips. At this stage, the chips are separate, but are still mounted on the glass blank. This step is shown in Fig. 135.
34. Detach the chips from the glass blank. Strip all adhesive, resist, sacrificial, and exposed seed layers. This step is shown in Fig. 136.
35. Mount the print heads in their packaging, which may be a molded plastic former incorporating ink channels which supply different colors of ink to the appropriate regions of the front surface of the wafer. The package also includes a piezoelectric actuator attached to the rear of the ink channels. The piezoelectric actuator provides the oscillating ink pressure required for the ink jet operation.
36. Connect the print heads to their interconnect systems.
37. Hydrophobize the front surface of the print heads.
38. Fill the completed print heads with ink and test them. A filled nozzle is shown in Fig. 137.

IJ USES

[0030] 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

[0031] The embodiments of the invention use an ink jet printer type device. Of course many different devices could be used. However presently popular ink jet printing technologies are unlikely to be suitable.
[0032] 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.

[0033] 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 pagewide print heads with 19,200 nozzles.

[0034] 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 per page).

[0035] 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.

[0036] 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

[0037] 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.

[0038] 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

[0039] The following table is a guide to cross-reference 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	IJ02	Electrostatic Ink Jet Printer
IJ03US	IJ03	Planar Thermoelastic Bend Actuator Ink Jet
IJ04US	IJ04	Stacked Electrostatic Ink Jet Printer
IJ05US	IJ05	Reverse Spring Lever Ink Jet Printer
IJ06US	IJ06	Paddle Type Ink Jet Printer
IJ07US	IJ07	Permanent Magnet Electromagnetic Ink Jet Printer
IJ08US	IJ08	Planar Swing Grill Electromagnetic Ink Jet Printer
IJ09US	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	IJ12	Linear Stepper Actuator Ink Jet Printer

(continued)

Docket No.	Reference	Title
IJ13US	IJ13	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	IJ20	Curling Calyx Thermoelastic Ink Jet Printer
IJ21US	IJ21	Thermal Actuated Ink Jet Printer
IJ22US	IJ22	Iris Motion Ink Jet Printer
IJ23US	IJ23	Direct Firing Thermal Bend Actuator Ink Jet Printer
IJ24US	IJ24	Conductive PTFE Ben Activator Vented Ink Jet Printer
IJ25US	IJ25	Magnetostrictive Ink Jet Printer
IJ26US	IJ26	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
IJ30US	IJ30	Thermoelastic Bend Actuator Using PTFE and Corrugated Copper Ink Jet Printer
IJ31US	IJ31	Bend Actuator Direct Ink Supply Ink Jet Printer
IJ32US	IJ32	A High Young's Modulus Thermoelastic Ink Jet Printer
IJ33US	IJ33	Thermally actuated slotted chamber wall ink jet printer
IJ34US	IJ34	Ink Jet Printer having a thermal actuator comprising an external coiled spring
IJ35US	IJ35	Trough Container Ink Jet Printer
IJ36US	IJ36	Dual Chamber Single Vertical Actuator Ink Jet
IJ37US	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	IJ40	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
IJ42US	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

[0040] 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.

[0041] 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)

[0042] 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.

[0043] Other inkjet configurations can readily be derived from these 45 examples by substituting alternative configurations 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.

[0044] 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.

[0045] 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 format printers, Notebook PC printers, Fax machines. Industrial printing systems, Photocopiers, Photographic minilabs etc.

[0046] The information associated with the aforementioned 11 dimensional matrix are set out in the following tables.

Actuator mechanism (applied only to selected ink drops)

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 ♦ IJ4
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 used low strain ♦ Response speed is marginal (~ 10 μs) ♦ High voltage drive transistors required ♦ Full pagewidth print heads impractical due to actuator size	♦ Seiko Epson, Usui et all 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 μs) ♦ 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 used 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 electro-magnetic	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 used 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 ♦ Operating temperature limited to the 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 Lorenz force	The Lorenz 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
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

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
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
Thermoelastic bend actuator	An actuator which relies upon differential thermal expansion upon Joule beating 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, IJ31, IJ32 ♦ IJ33, IJ34, IJ35, IJ36 ♦ IJ37, IJ38, IJ39, IJ40 ♦ IJ41

(continued)

Actuator Mechanism	Description	Advantages	Disadvantages	Examples
High CTE thermoelastic actuator	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 μ m long PTFE bend actuator with polysilicon heater and 15 mW power input can provide 180 μN force and 10 μm deflection. Actuator motions include: 1) Bend 2) Push 3) Buckle 4) Rotate	♦ High force can be generated ♦ PTFE is a candidate for low dielectric constant insulation in ULSI ♦ 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 material (e.g. PTFE) ♦ 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 ♦ Pigmented inks may be infeasible, as pigment particles may jam the bend actuator	♦ IJ09, IJ17, IJ18, IJ20 ♦ IJ21, IJ22, IJ23, IJ24 ♦ IJ27, IJ28, IJ29, IJ30 ♦ IJ31, IJ42, IJ43, IJ44
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 austenic state. The shape of the actuator in its martensitic state is deformed relative to the austenic 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-suessing 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

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, IJ4 ♦ IJ05, IJ06, IJ07, IJ09 ♦ IJ11, IJ12, IJ14, IJ16 ♦ IJ20, IJ22, IJ23, IJ24 ♦ IJ25, IJ26, IJ27, IJ28 ♦ 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
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

(continued)

Operational mode	Description	Advantages	Disadvantages	Examples
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
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

Auxiliary mechanism (applied to all nozzles)

Auxiliary 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, IJ20, 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
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 IJ series

(continued)

Auxiliary Mechanism	Description	Advantages	Disadvantages	Examples
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 Lorenz 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
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

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

(continued)

Actuator amplification	Description	Advantages	Disadvantages	Examples
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, IJ44
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
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, IJ20 ♦ IJ22, IJ28, IJ42, IJ43
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

(continued)

Actuator amplification	Description	Advantages	Disadvantages	Examples
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 orientations.	♦ IJ17, IJ21, IJ34, IJ35
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, IJ33
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

(continued)

Actuator amplification	Description	Advantages	Disadvantages	Examples
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
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

(continued)

Tapered magnetic pole	A tapered magnetic pole can increase travel at the expense of force.	♦ Linearizes the magnetic force/ distance curve	♦ Complex construction	♦ IJ14
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

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 kogation in thermal ink jet implementations	♦ Hewlett-Packard Thermal Inkjet ♦ Canon Bubblejet
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, IJ13, IJ15, IJ33, ♦ IJ34, IJ35, 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

(continued)

Actuator motion	Description	Advantages	Disadvantages	Examples
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, IJ29 ♦ 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 austenic phase is planar	♦ Requires careful balance of stresses to ensure that the quiescent bend is accurate	♦ IJ26, IJ32
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 3,693,212
Coil/uncoll	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, 1J21, IJ34, IJ35

(continued)

Actuator motion	Description	Advantages	Disadvantages	Examples
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
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

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 form 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
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

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 ♦ Operational simplicity ♦ Reduces crosstalk	♦ Restricts refill rate ♦ May result in a relatively large chip area ♦ Only partially effective	♦ Thermal inkjet ♦ 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, IJ09-IJ12 ♦ IJ14, IJ16, IJ20, IJ22, ♦ IJ23-IJ34, IJ36-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

(continued)

Inlet back-flow restriction method	Description	Advantages	Disadvantages	Examples
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
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, IJ12, IJ24, IJ27 ♦ IJ29, IJ30
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, IJ06 ♦ IJ07, IJ10, IJ11, IJ14 ♦ IJ16, IJ22, IJ23, IJ25 ♦ IJ28, IJ31, IJ32, IJ33 ♦ IJ34, IJ35, IJ36, IJ39 ♦ IJ40, IJ41

(continued)

Inlet back-flow restriction method	Description	Advantages	Disadvantages	Examples
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
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

<u>Nozzle Clearing Method</u>

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, IJ27 ♦ 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 e-ection 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 U series ink jets

Nozzle plate construction

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
M**onolithic, 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, IJ04, IJ11 ♦ IJ12, IJ17, IJ18, IJ20 ♦ IJ22, IJ24, IJ27, IJ28 ♦ IJ29, IJ30, IJ31, IJ32 ♦ IJ33, IJ34, IJ36, IJ37 ♦ IJ38, IJ39, IJ40, IJ41 ♦ IJ42, IJ43, IJ44

(continued)

Nozzle plate construction	Description	Advantages	Disadvantages	Examples
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 entirety, 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
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

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 handing	♦ 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 4,999,181 ♦ 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 TU 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
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

Ink type	Description	Advantages	Disadvantages	Example
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 mechanisms ♦ Cockles paper	♦ IJ02, IJ04, IJ21, IJ26 ♦ IJ27, IJ30 actuator ♦ Silverbrook, 'EP 0771 658 A2 and related patent applications ♦ Piezoelectric ink-jets ♦ Thermal ink jets (with significant restrictions)
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

(continued)

Ink type	Description	Advantages	Disadvantages	Example
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 dies 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 U series ink jets

Ink Jet Printing

[0047] 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

[0048] Further, the present application may utilize advanced semiconductor fabrication techniques in the construction of large arrays of ink jet printers.

Fluid Supply

[0049] Further, the present application may utilize an ink delivery system to the ink jet head.

MEMS Technology

[0050] Further, the present application may utilize advanced semiconductor microelectromechanical techniques in the construction of large arrays of ink jet printers.

IR Technologies

[0051] Further, the present application may include the utilization of a disposable camera system

DotCard Technologies

[0052] Further, the present application may include the utilization of a data distribution system

Artcam Technologies

[0053] Further, the present application may include the utilization of camera and data processing techniques

[0054] 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 (710) comprising:

   an ink reservoir having means for providing an ink supply under a fluctuating pressure;
   a nozzle chamber (713) having an ink ejection port (714) for the ejection of ink drops onto a print media; and
   a shutter means (711,716) interconnecting said reservoir and said nozzle chamber (713), said shutter means being operable by means of electromagnetic actuation so as to control the ejection of ink from said ink ejection port (714), wherein said shutter means (711,716) is moveable across an aperture in a wall of said nozzle chamber (713).

2. An inkjet nozzle (710) as claimed in claim 1, wherein said shutter means comprises an arm (716) interconnected to at least one shutter (711).

3. An inkjet nozzle (710) as claimed in claim 2 further comprising an electromagnet (719) for moving said arm (716), thereby opening a channel for the flow of ink.

4. An ink jet nozzle (710) as claimed in claim 3 wherein said electromagnet (719) includes a first (726) and second end (727) and wherein each of said ends are positioned closely adjacent to said arm (716) and said electromagnetic actuation includes movement of said arm closer to both of said ends.

5. An inkjet nozzle (710) as claimed in claim 2 wherein said arm (716) is pivoted between said first and second ends (726,727) of said electromagnet (719).

6. An ink jet nozzle (710) as claimed in any of claims 3 to 5 wherein the electromagnet (719) has a spiral shape.

7. An ink jet nozzle (710) as claimed in any of claims 1 to 6 further comprising:

   a resilient means (730) connected to said shutter means, said resilient means being elastically deformed by said electromagnetic actuation and said resilient means operating to return to an initial state upon deactivation of said shutter means so as to restrict the further flow of fluid from said ink reservoir to said nozzle chamber (713).

8. An ink jet nozzle (710) as claimed in claim 7 wherein said resilient means comprises a coiled spring (730).

9. An ink jet nozzle (710) as claimed in any of claims 3 to 8 wherein said electromagnet (719) is formed utilizing semiconductor fabrication techniques from a copper coil (721) surrounding a soft metal core (720).

10. An ink jet nozzle (710) as claimed in claim 9 wherein said copper coil (721) is formed from utilizing a damascene process.

Patentansprüche

1. Tintenstrahldüse (710), umfassend:

   einen Tintenbehälter mit einer Einrichtung, um unter schwankendem Druck eine Tintenzufuhr bereitzustellen;
   eine Düsenkammer (713) mit einer Tintenausstoßöffnung (714) zum Ausstoßen von Tintentröpfchen auf ein Druckmedium; und
   ein Verschlusseinrichtung (711, 716), die den Behälter und die Düsenkammer (713) verbindet, wobei die Ver-

schlusseinrichtung durch elektromagnetische Betätigung betrieben werden kann, um das Ausstoßen von Tinte aus der Tintenausstoßöffnung (714) zu steuern, wobei die Verschlusseinrichtung (711, 716) über eine Öffnung in einer Wand der Düsenkammer (713) bewegbar ist.

2. Tintenstrahldüse (710) nach Anspruch 1, wobei die Verschlusseinrichtung einen Arm (716) umfasst, der mit wenigstens einer Verschlusseinrichtung verbunden ist.

3. Tintenstrahldüse (710) nach Anspruch 2, darüber hinaus einen Elektromagneten (719) zum Bewegen des Arms (716) umfassend, wodurch ein Kanal für den Tintenstrom geöffnet wird.

4. Tintenstrahldüse (710) nach Anspruch 3, wobei der Elektromagnet (719) ein erstes (726) und zweites Ende (727) umfasst und jedes der Enden nahe neben dem Arm (716) angeordnet ist, und die elektromagnetische Betätigung beinhaltet, den Arm näher an beide Enden heranzubringen.

5. Tintenstrahldüse (710) nach Anspruch 2, wobei der Arm (716) zwischen dem ersten und zweiten Ende (726, 727) des Elektromagneten (719) schwenkbar ist.

6. Tintenstrahldüse (710) nach einem der Ansprüche 3 bis 5, wobei der Elektromagnet (719) eine spiralförmige Gestalt hat.

7. Tintenstrahldüse (710) nach einem der Ansprüche 1 bis 6, darüber hinaus umfassend:

eine Federeinrichtung (730), die mit der Verschlusseinrichtung verbunden ist, wobei die Federeinrichtung durch die elektromagnetische Betätigung elastisch verformt wird und die Federeinrichtung so arbeitet, dass sie bei Deaktivierung der Verschlusseinrichtung in einen Ausgangszustand zurückkehrt, um den weiteren Fluidstrom vom Tintenbehälter zur Düsenkammer (713) zu drosseln.

8. Tintenstrahldüse (710) nach Anspruch 7, wobei die Federeinrichtung eine Wickelfeder (730) umfasst.

9. Tintenstrahldüse (710) nach einem der Ansprüche 3 bis 8, wobei der Elektromagnet (719) aus einer einen Weichmetallkern (720) umgebenden Kupferspule (721) unter Anwendung von Techniken aus der Halbleiterherstellung gebildet ist.

10. Tintenstrahldüse (710) nach Anspruch 9, wobei die Kupferspule (721) unter Anwendung eines Damaszener-Verfahrens gebildet wird.

Revendications

1. Buse de jet d'encre (710) comprenant :

un réservoir d'encre ayant des moyens pour fournir une alimentation en encre sous une pression fluctuante ;
une chambre de buse (713) ayant un port d'éjection d'encre (714) pour l'éjection de gouttes d'encre sur un support d'impression ; et
des moyens d'obturation (711, 716) interconnectant ledit réservoir et ladite chambre de buse (713), lesdits moyens d'obturation pouvant être actionnés au moyen d'une commande électromagnétique de manière à commander l'éjection d'encre depuis ledit port d'éjection d'encre (714), dans lequel lesdits moyens d'obturation (711, 716) sont mobiles à travers une ouverture dans une paroi de ladite chambre de buse (713).

2. Buse de jet d'encre (710) comme revendiqué dans la revendication 1, dans laquelle lesdits moyens d'obturation comportent un bras (716) interconnecté à au moins un obturateur (711).

3. Buse de jet d'encre (710) comme revendiqué dans la revendication 2 comportant en outre un électro-aimant (719) pour déplacer ledit bras (716), ouvrant ainsi un canal pour le flux d'encre.

4. Buse de jet d'encre (710) comme revendiqué dans la revendication 3 dans laquelle ledit électro-aimant (719) inclut une première (726) et une seconde (727) extrémités et dans laquelle chacune desdites extrémités est positionnée à proximité proche dudit bras (716) et ladite commande électromagnétique inclut un rapprochement dudit bras de chacune des deux dites extrémités.

5. Buse de jet d'encre (710) comme revendiqué dans la revendication 2 dans laquelle ledit bras (716) est pivoté entre lesdites première et deuxième extrémités (726, 727) dudit électro-aimant (719).

6. Buse de jet d'encre (710) comme revendiqué dans l'une quelconque des revendications 3 à 5 dans lequel l'électro-aimant (719) a une forme de spirale.

7. Buse de jet d'encre (710) comme revendiqué dans l'une quelconque des revendications 1 à 6 comprenant en outre

des moyens élastiques (730) connectés auxdits moyens d'obturation, lesdits moyens élastiques étant élastiquement déformés par ladite commande électromagnétique et lesdits moyens élastiques fonctionnant pour revenir à un état initial suite à la désactivation desdits moyens d'obturation de manière à restreindre le flux suivant de fluide depuis ledit réservoir d'encre vers ladite chambre de buse (713).

8. Buse de jet d'encre (710) comme revendiqué dans la revendication 7 dans laquelle lesdits moyens élastiques comportent un ressort à bobine (730).

9. Buse de jet d'encre (710) comme revendiqué dans l'une quelconque des revendications 3 à 8 dans laquelle ledit électro-aimant (719) est formé en utilisant des techniques de fabrication de semi-conducteur d'une bobine de cuivre (721) entourant un noyau en métal doux (720).

10. Buse de jet d'encre (710) comme revendiqué dans la revendication 9 dans laquelle ladite bobine de cuivre (721) est formée en utilisant un procédé de damasquinage.

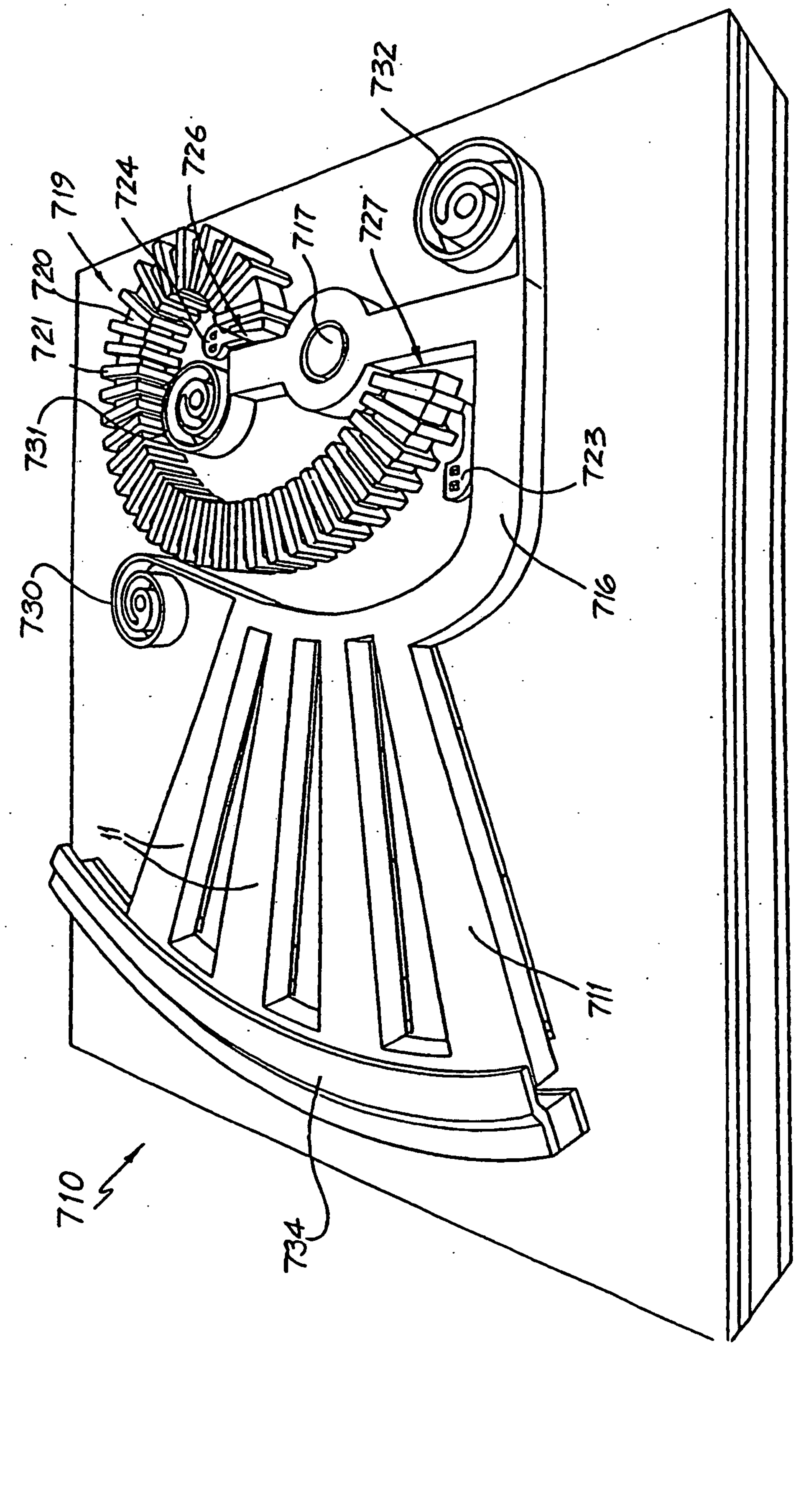

FIG. 112

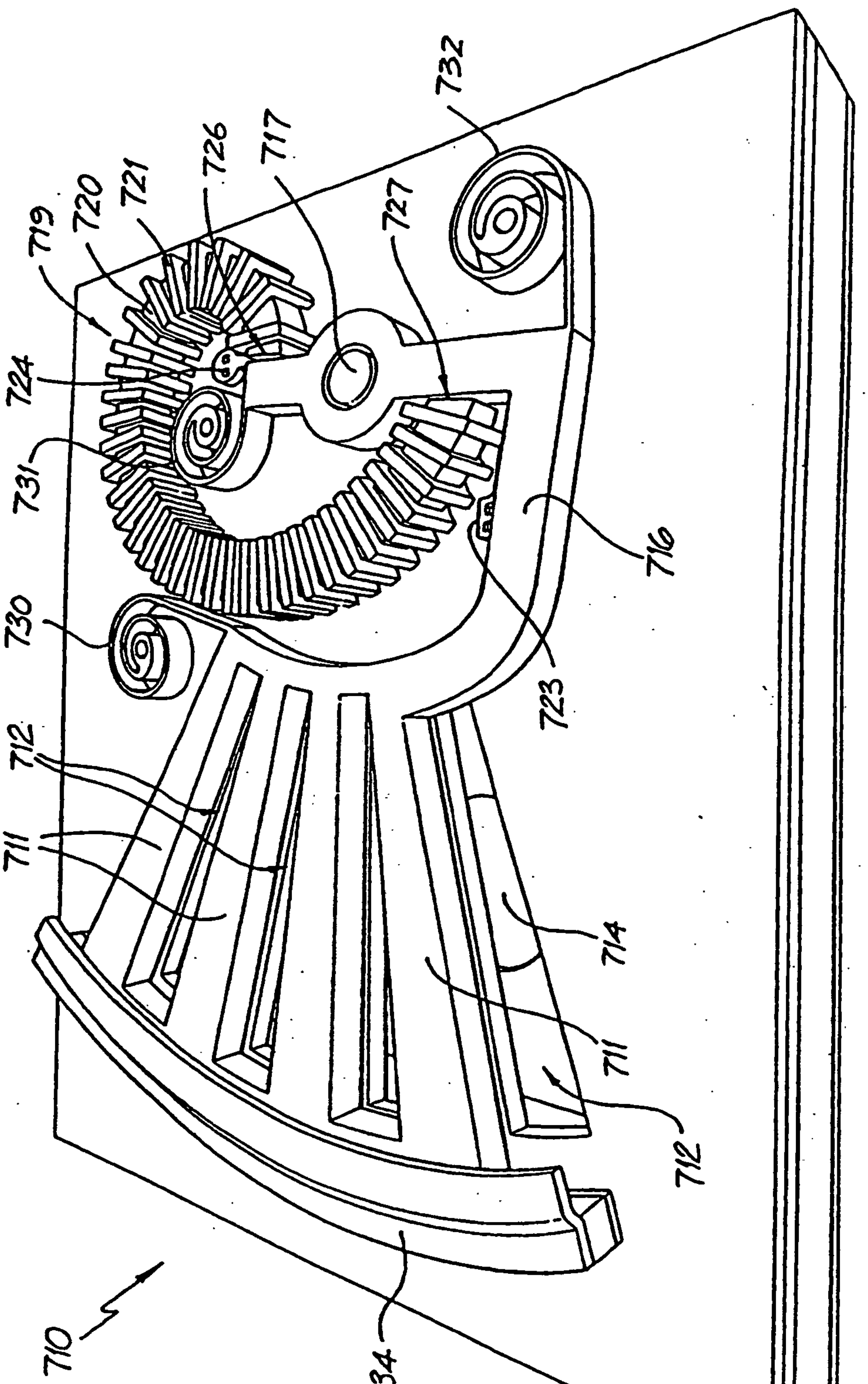
710
711
712
714
716
717
719
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FIG. 113

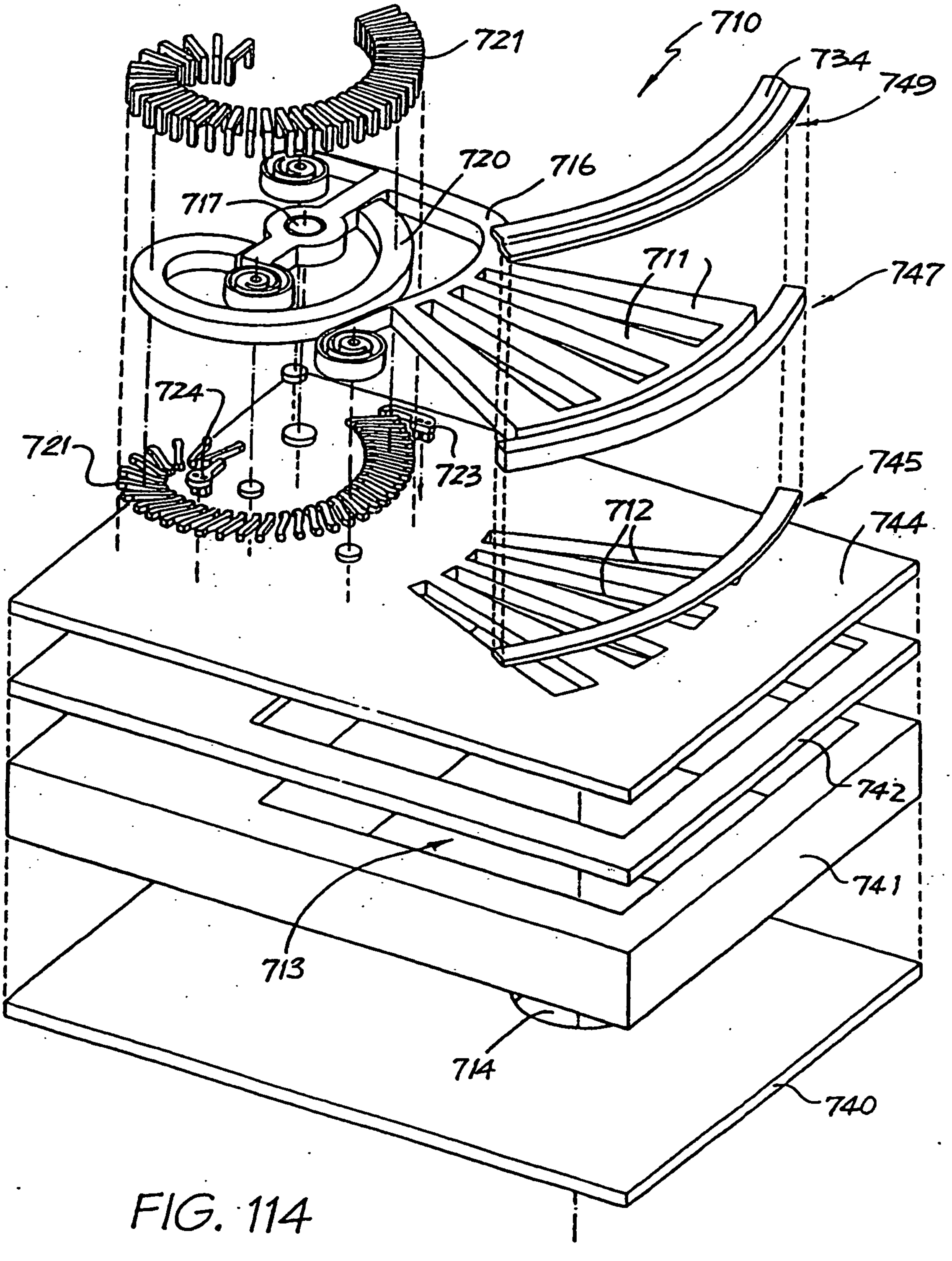
710
721
734
749
720
716
717
711
747
724
721
723
745
712
744
742
741
713
714
740

FIG. 114

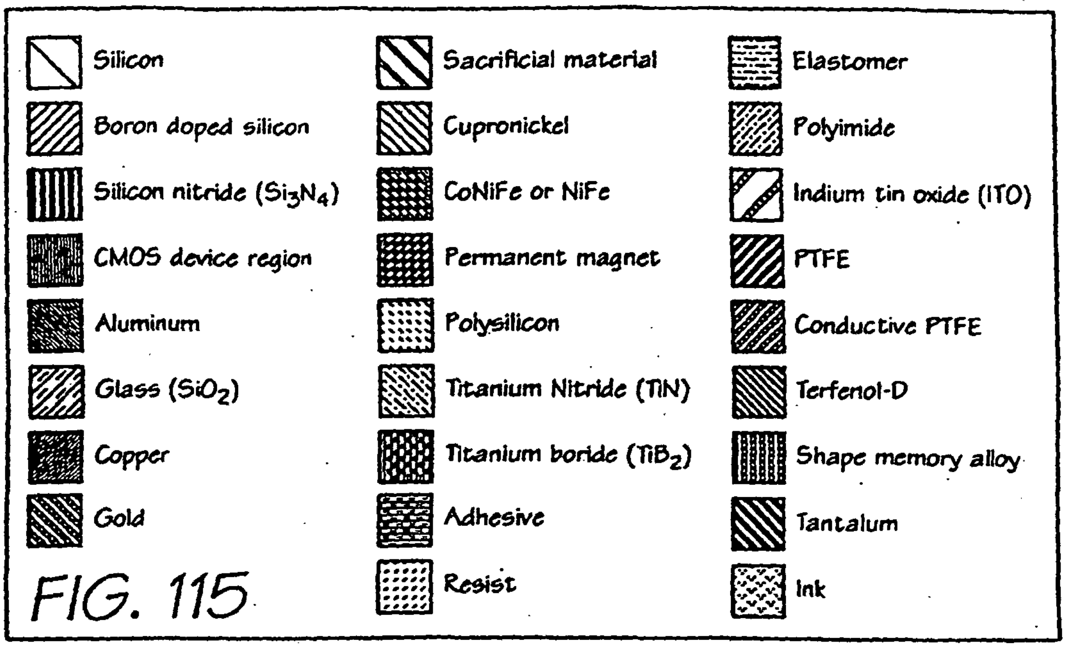

FIG. 115

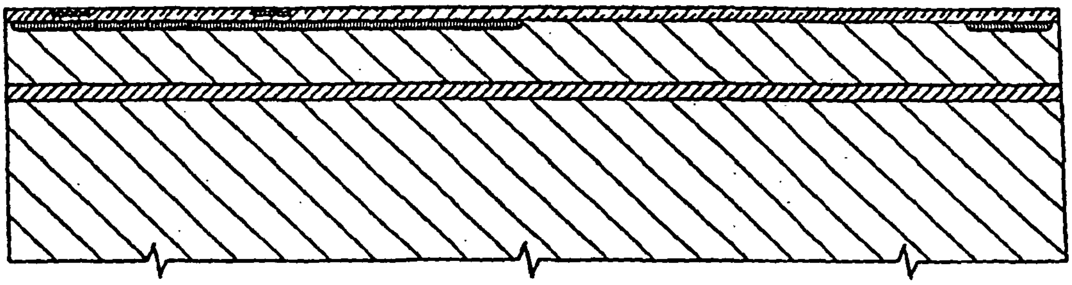
FIG. 116

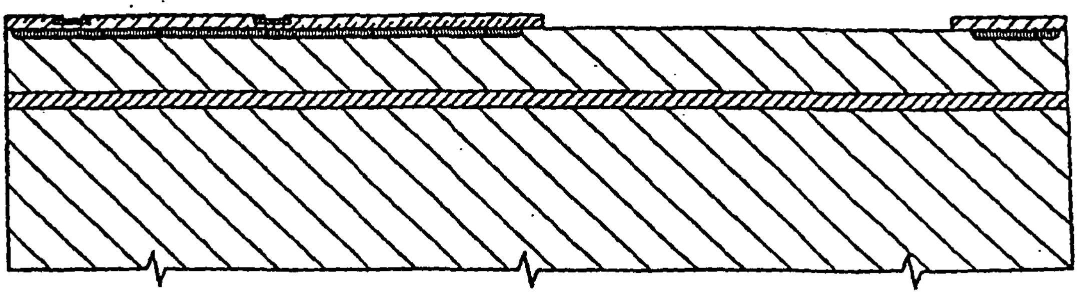
FIG. 117

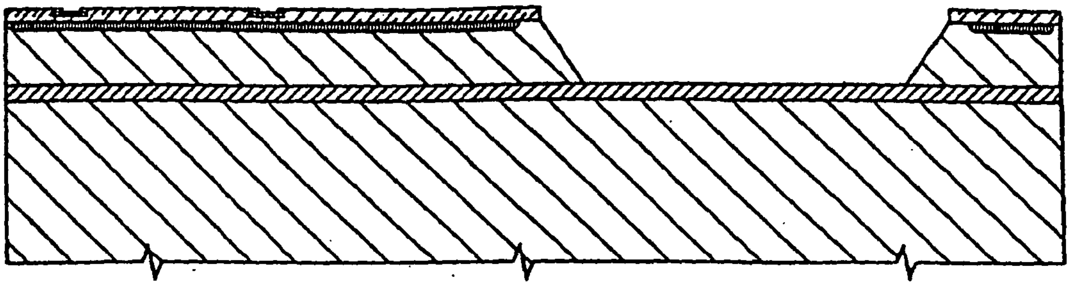

FIG. 118

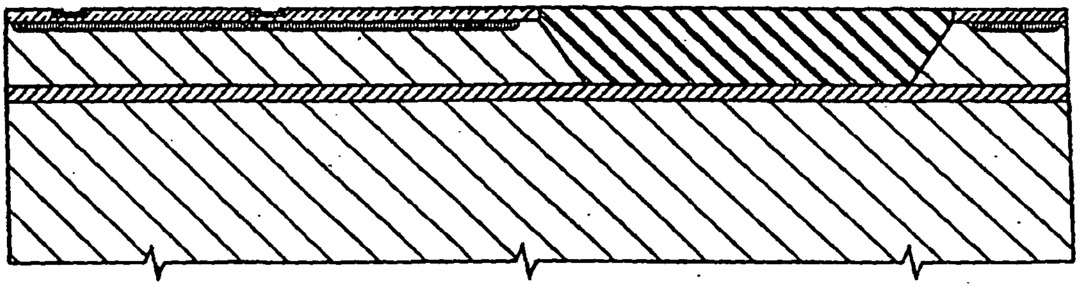

FIG. 119

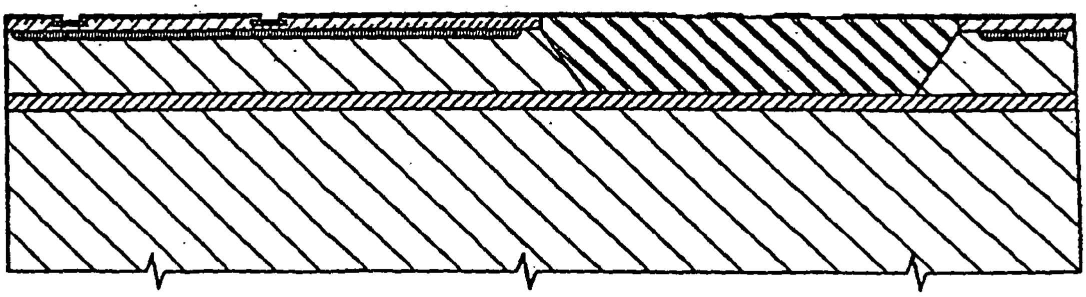

FIG. 120

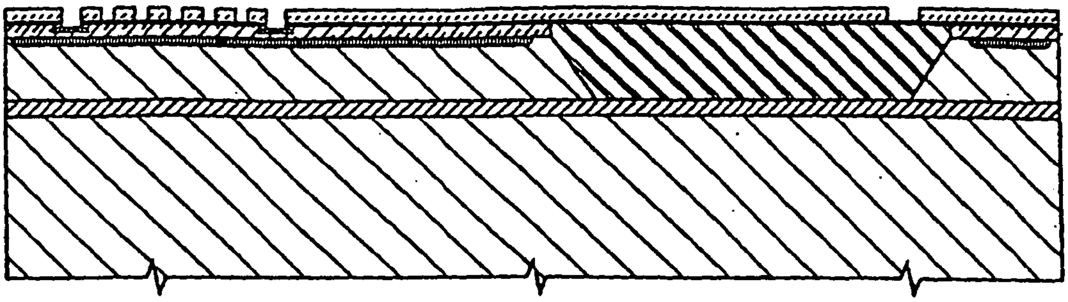

FIG. 121

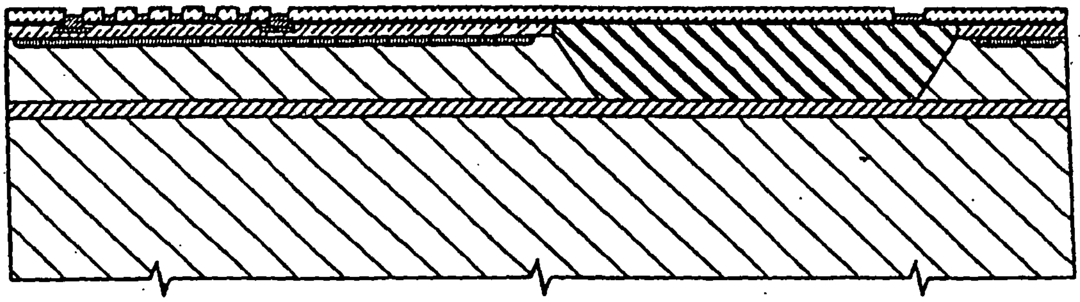

FIG. 122

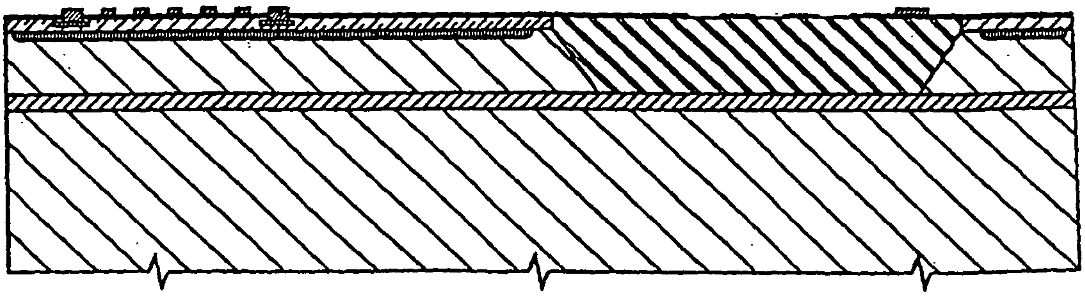

FIG. 123

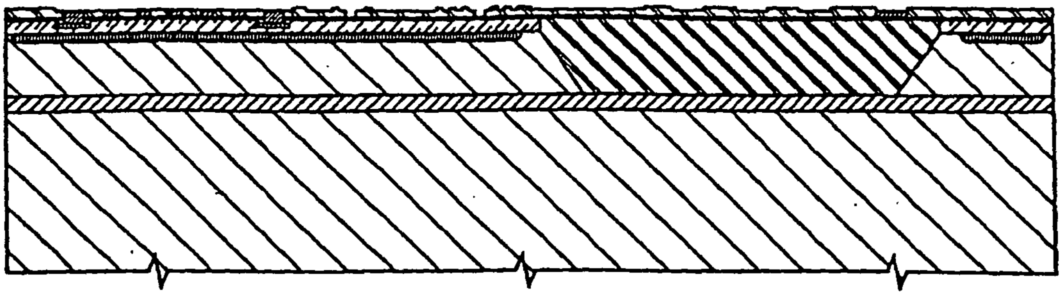

FIG. 124

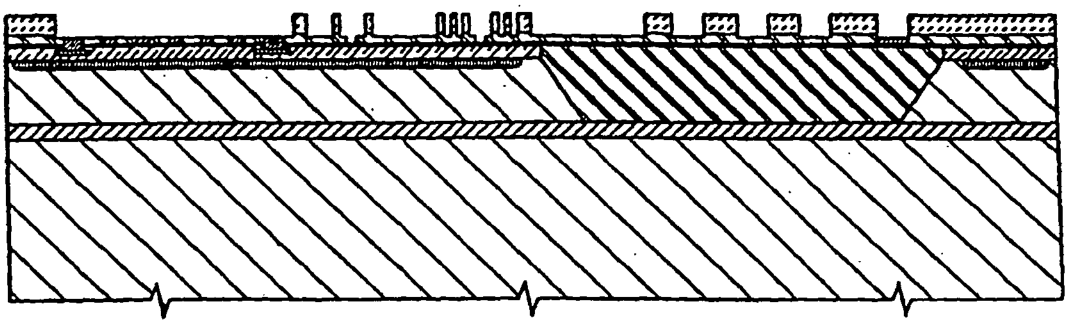

FIG. 125

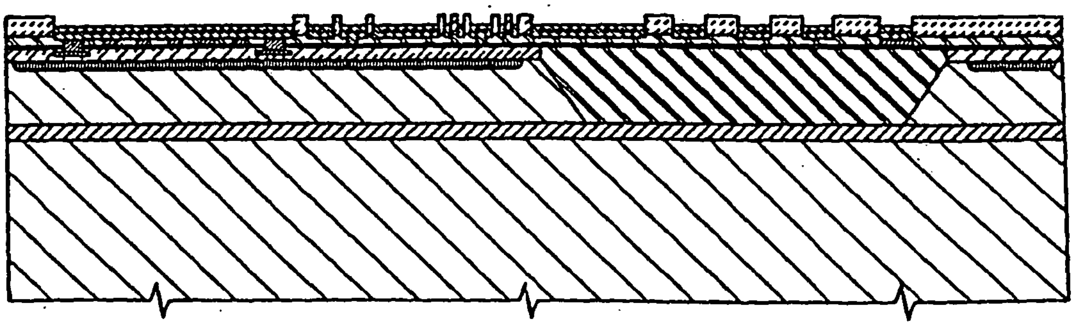

FIG. 126

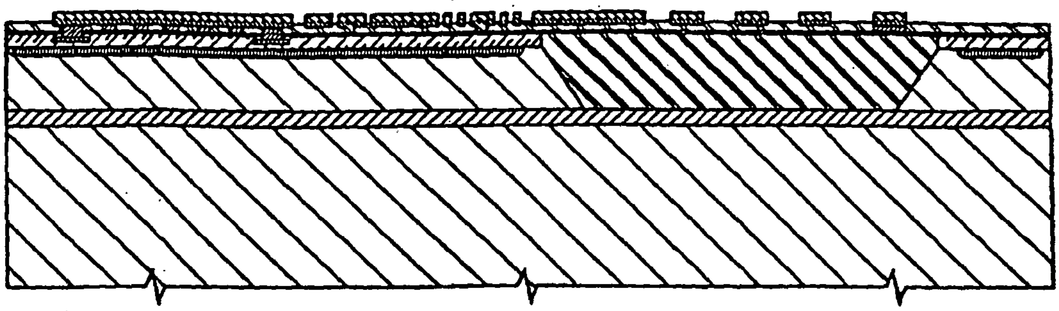

FIG. 127

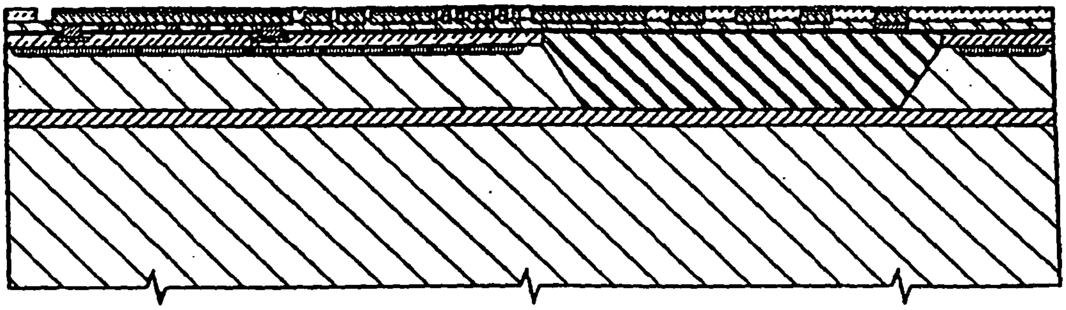

FIG. 128

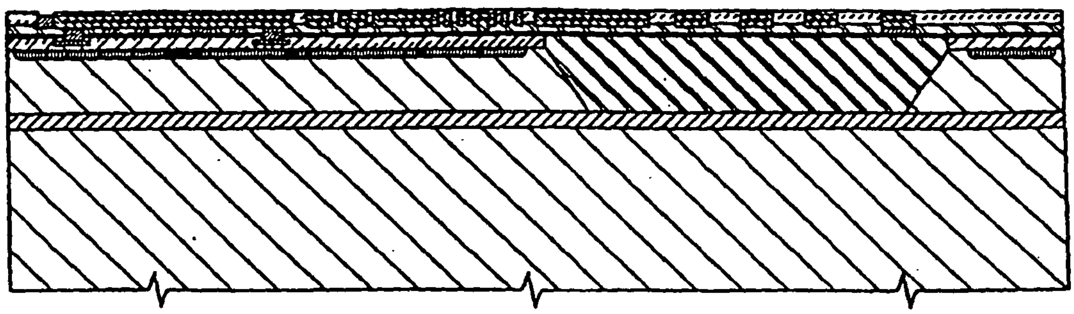

FIG. 129

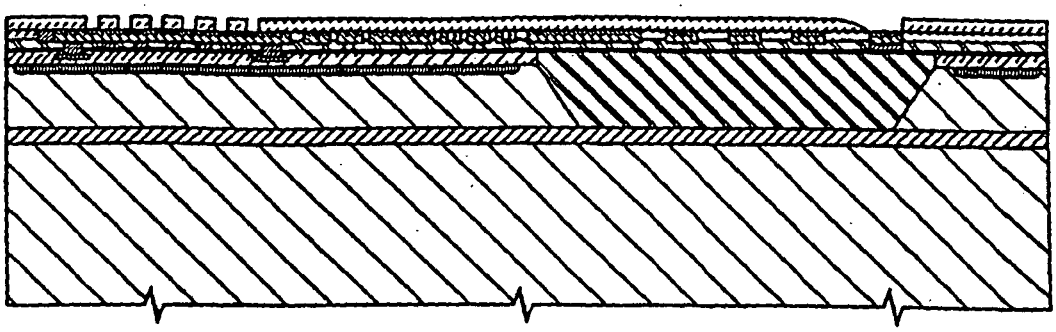

FIG. 130

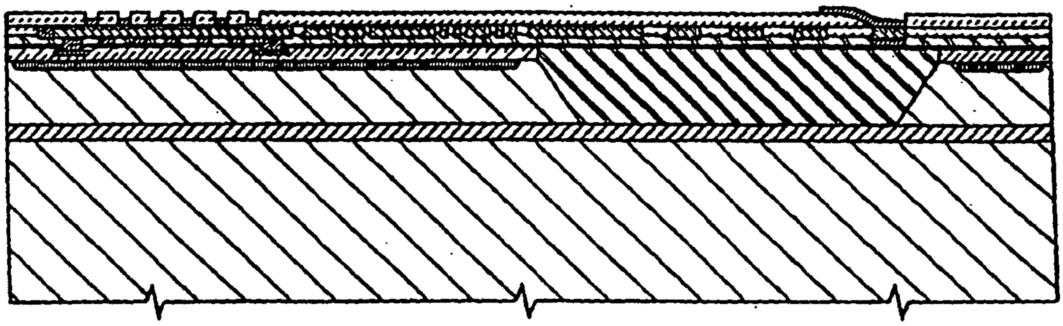

FIG. 131

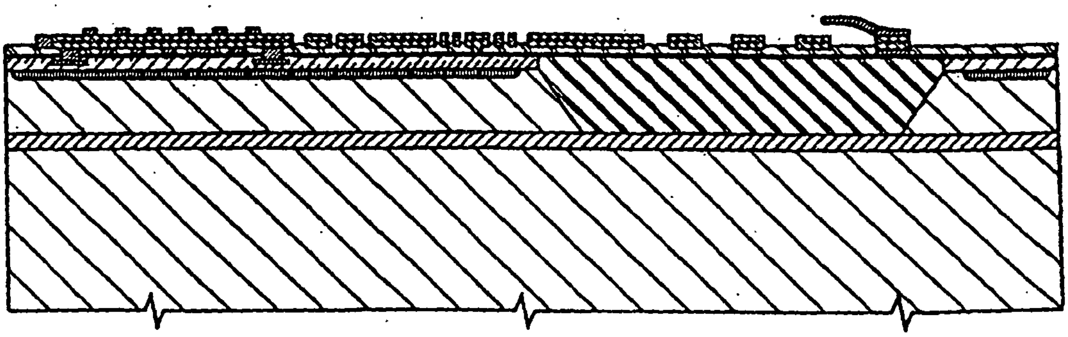

FIG. 132

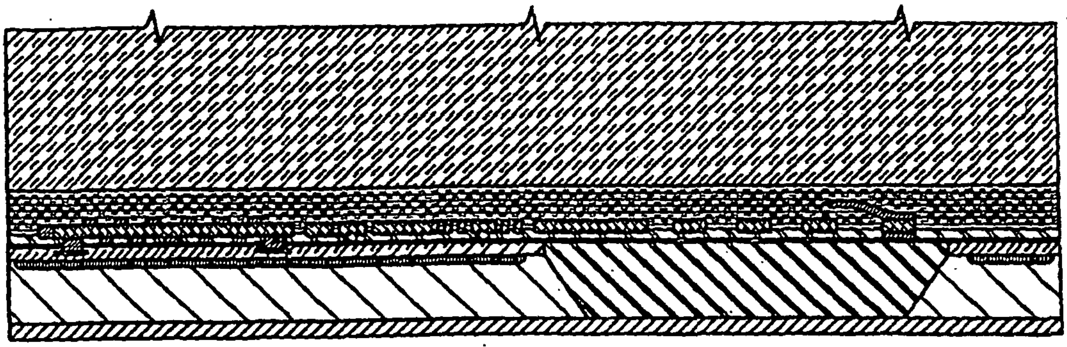

FIG. 133

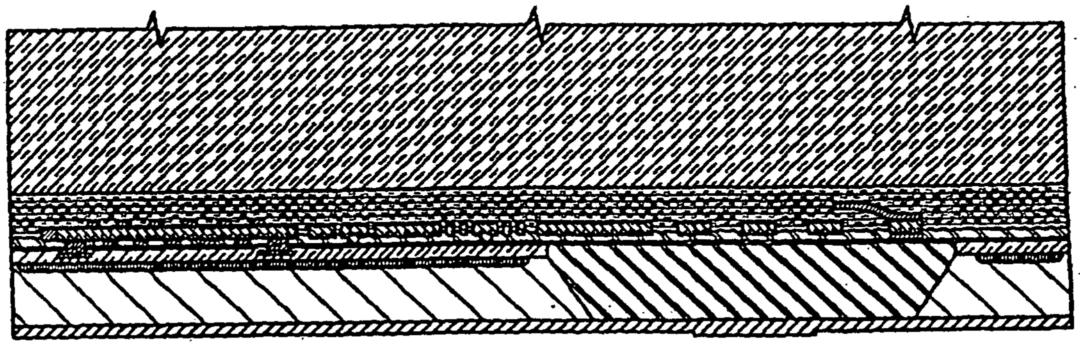

FIG. 134

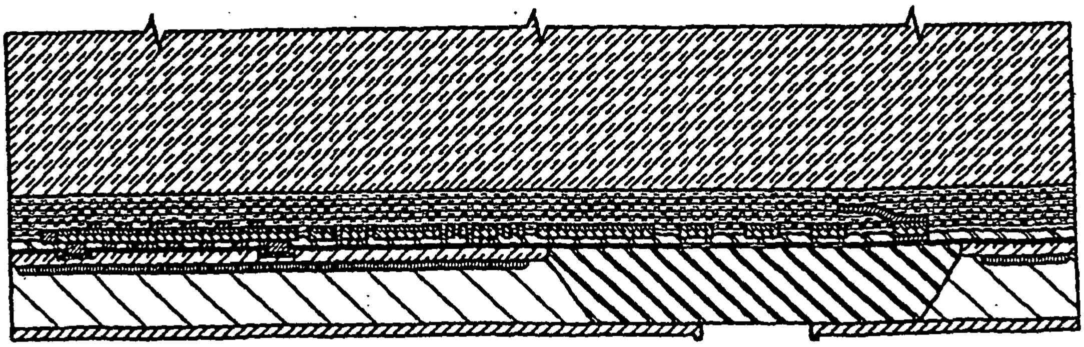

FIG. 135

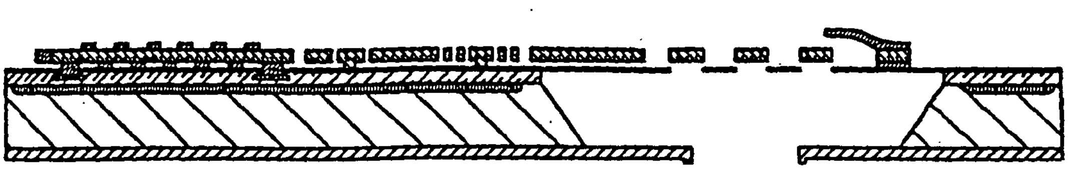

FIG. 136

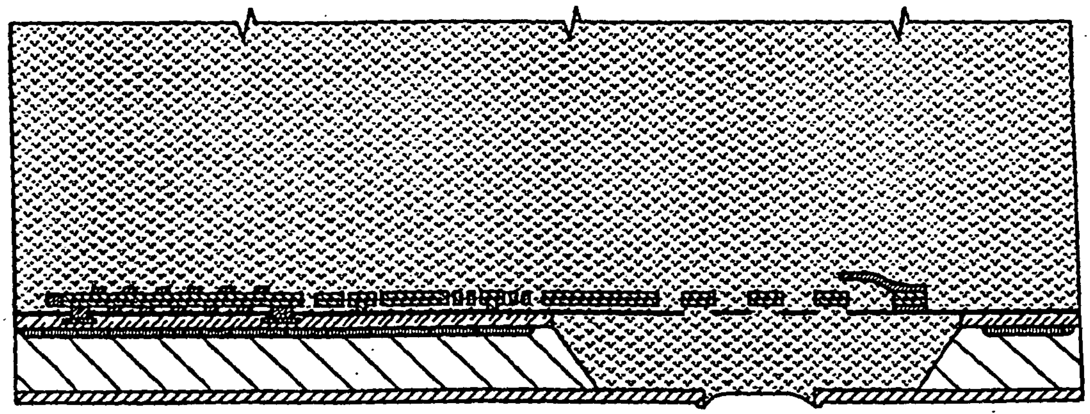

FIG. 137