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(54) **Droplet ejections by acoustic and electrostatic forces.**

(57) A technique for ejecting droplets using acoustic radiation and electrostatic attraction. Ejection proceeds by acoustically raising a mound (14) of ink (18) proximate an electrode (20) and then electrostatically attracting the mound by applying a voltage to the electrode. The electric field further accelerates the mound and, since the raised mound has a restricted volume, a Rayleigh instability necks off the mound, thereby creating a droplet (12). The droplet is ejected onto a recording medium (34) by the momentum imparted to the droplet by the acoustic energy and the electrostatic force. Beneficially, the applications of the acoustic energy and the electrode voltage are used to address the ejecting droplet ejector. Droplet ejectors in a column (or row) form a column (or row) of mounds, while an electrode voltage is applied to each of the electrodes of a row (or columns) of droplet ejectors. Only the droplet ejector associated with an acoustically raised a mound and with an energized electrode ejects a droplet.

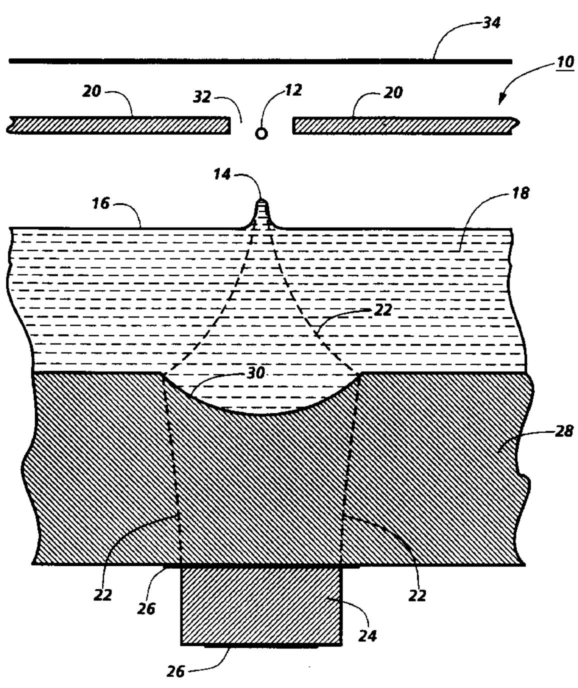

Fig. 1

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The present invention relates generally to acoustic droplet ejection.

Various ink jet printing technologies have been developed. One such technology, referred to hereinafter as acoustic ink printing (AIP), produces an image on a recording medium via acoustic energy. While more detailed descriptions of the AIP process can be found in US-A-4,308,547, 4,697,195, and 5,028,937, essentially, bursts of acoustic radiation focused near the free surface of a liquid ink cause ink droplets to be ejected onto a recording medium.

To produce high quality images using AIP, the ink droplets must be closely spaced, which requires densely packed droplet ejectors. The typical manner of arranging droplet ejectors is to (1) form rows of equally spaced droplet ejectors, (2) arrange the rows such that they are adjacent and such that the droplet ejectors in adjacent rows form offset columns, and (3) electrically interconnect the ejectors into an X-Y planar array of rows and columns. To eject a droplet from any particular droplet ejector, that ejector is addressed by the application of drive signals to that droplet ejector's row and column conductors. While this scheme is generally successful, as the density of droplet ejectors increases, the planar area available for the required electrical conductors decreases. A possible method of increasing droplet ejector density would be to reduce the planar area required for the electrical conductors. However, this would require a different addressing scheme for the droplet ejectors. Therefore, an addressing technique which enables an increase in droplet ejector density would be beneficial.

It is to be noted that G. Taylor in "Disintegration of water drops in an electric field," Proc. Roy. Soc. A, 280, pp. 383-397, 1964, showed analytically and experimentally that, in certain geometries, a strong electrostatic field (E-field) will pull a flat liquid surface into a cone having a half angle of 49.3°; such cones are commonly referred to as "Taylor cones." Experiments have shown that the formation of a cone on a flat pool of ink takes on the order of seconds (about 1 to 10 for reasonable E-field levels), whereas once formed they collapse within about 50 msec after removal of the E-field. The slow formation of cones is believed to be related to the relatively large gap between the cone forming electrode and the liquid during the early stages of cone formation. Consequently, as the gap narrows, the E-field begins concentrating near the apex of the cone and the rate at which the cone forms increases. Supporting this hypothesis are experiments that indicate that the final formation of a cone occurs very rapidly in some E-fields, in much less than 15 msec.

As Taylor observed and as further experimentation has confirmed, some E-field values cause material to be ejected from the cone's apex, usually in the form of a stream or jet. A somewhat related effect has also been found to occur. If one attempts to form a cone on a pool of liquid very quickly, a catastrophic ejection of material from the rather large volume of liquid comprising the resulting "cone" occurs. Such catastrophic ejections are to be avoided in AIP since the volume of ink in such an ejection is much greater than the desired ink droplet volume. However, a technique for reducing the volume of material ejected would enable cone formation to be used in AIP.

It is an object of the present invention to provide a technique for acoustically ejecting low volume droplets by using cone formation.

According to one aspect of the invention, there is provided a method of ejecting a droplet comprising the steps of acoustically forming a mound on the free surface of a liquid; and electrostatically attracting the liquid in the mound until a Rayleigh instability necks off the mound to form and eject a droplet.

According to another aspect, the invention provides a droplet ejector for ejecting a droplet from the free surface of a liquid onto a recording medium, said droplet ejector comprised of an ink well for holding a liquid such that said liquid has a free surface; means for acoustically forming a mound on the free surface of the liquid; and means for electrostatically attracting the liquid in said mound until a Rayleigh instability necks off the mound to form and eject a droplet onto the recording medium.

The invention also provides a method of selectively ejecting droplets from a plurality of droplet ejectors arranged in an array of rows and columns, each of the droplet ejectors comprising an acoustic transducer and an electrode, the method comprising the steps of acoustically forming a column of mounds on the free surface of a liquid; and radiating electrostatically attractive forces from a row of the electrodes such that a droplet is ejected from one of said acoustically raised mounds.

Beneficially, the invention is implemented in a manner such that cone formation assists in the addressing of the ejecting droplet ejector, thereby reducing the required electrical interconnection area, and thus enabling denser packing of the droplet ejectors. The ejection technique involves acoustically raising a mound of ink proximate an electrode and then rapidly applying an E-field to the mound. Since such an acoustically raised mound has a restricted volume (having a diameter on the order of the acoustic wavelength), the applied E-field creates a Rayleigh instability which necks off the mound, thereby forming a droplet which is ejected from the mound because of the combined momentum imparted to the droplet by the acoustic radiation and the electrode voltage. The addressing technique involves acoustically forming a column (or alternatively a row) of mounds and then selecting the ejecting droplet ejector by applying a voltage to all of the electrodes of a row (or alternatively a column) of droplet ejectors about when the acoustically raised mounds approach their apexes. Only the droplet ejectors having both an acoustically raised mound and an applied electrode voltage eject droplets.

Other aspects of the present invention will become apparent as the following description proceeds and upon reference to the drawings, in which:

FIG. 1 shows a simplified, cross-sectional view of a droplet ejector according to the principles of the present invention;

FIG.2 shows an alternative embodiment droplet ejector (in simplified cross-section) according to the principles of the present invention; and

FIG. 3 illustrates an X-Y addressing scheme for an array of droplet ejectors according to FIG. 1.

Note that in the drawings like references designate like elements.

Refer now to Fig. 1, wherein an acoustic ink droplet ejector 10 according to the principles of the present invention is illustrated in cross-section. Basically, an ink droplet 12 is ejected from a mound 14 that is acoustically raised on the free surface 16 of a pool of ink 18 by the application of a voltage to an electrode 20 (shown in two parts in the cross-sectional view of FIG. 1) located near the mound. "Near" means a physical proximity such that the yet-to-be-described electrode voltage induces droplet ejection. The optimum proximity depends upon factors such as the ink's characteristics, the voltage applied to the electrodes, the acoustic energy which creates the mound, and the droplet ejection rate.

The acoustic radiation 22 that raises the mound 14 is generated by a transducer 24 that receives RF drive power via its terminals 26. The acoustic radiation passes through a body 28 (beneficially pyrex glass) until it reaches an acoustic lens 30. While the illustrated acoustic lens is a spherical lens, a Fresnel lens will also work. In any event, the acoustic lens focuses the acoustic radiation into a small focal area near the free surface 16. Of course, the depth of the ink and the dimensions of the acoustic lens and body 28 are controlled so that the focal area is near the free surface 16.

The operation of the droplet ejector 10 depends upon acoustically forming a mound with an apex near the electrode 20, and upon the application of voltage to that electrode. The acoustic radiation 22 intensity is controlled so that while it is sufficient to form the mound, it is not by itself sufficient to eject a droplet. As the mound forms, momentum is imparted to the ink and, as the apex approaches the electrode, the voltage applied to the electrode draws the ink toward the electrode, inducing more momentum. Since the mound has a limited volume, the mound deforms until a Rayleigh instability causes the mound to neck off, forming a droplet. The combined effect of the momentums imparted acoustically and electrostatically causes the formed droplet 12 to be ejected. The electrode 20 has an opening 32 through which the ejected droplet 12 passes on its way to being deposited on a recording medium 34.

An alternative embodiment droplet ejector 40 according to the principles of the present invention is shown in FIG. 2. The droplet ejector 40 is very similar to the droplet ejector 10 shown in FIG.1, except that the droplet ejector 40 has the electrode 20 positioned behind the recording medium 34, and the electrode 20 does not have an opening 32. Experiments indicate that, at least with some recording medias (such as paper), the electrostatic forces readily attract the ink 18 in the mounds 14 sufficiently to eject a droplet despite the interposed recording medium.

A practical acoustic ink printer will include a large number (possibly thousands) of individual droplet ejectors 10 physically and operatively organized into rows and columns. It is contemplated that the rows could extend the width of a printed page (say about 216mm (8.5 inches)) and have about 3 droplet ejectors per mm (75 per inch). The rows stack together such that columns of droplet ejectors are formed, with the columns being staggered at a slight angle (see FIG. 3 and the discussion below). This permits the effective linear density of the droplet ejectors to be much higher then 3 droplet ejectors per mm (75 per inch). For example, 8 such offset rows could yield a pixel pitch of 24 (8 times 3) per mm (600 (8 times 75) per inch) by moving the recording medium 34 (see FIG.s 1 and 2) in a controlled fashion while properly timing droplet ejection from the individual droplet ejectors. As previously explained, electrically interconnecting all of the droplet ejectors in a single plane tends to limit the droplet ejector density.

The use of acoustic radiation together with electrostatic attraction enables an increase in the droplet ejector density by reducing the planar area required for the interconnecting of the droplet ejectors. Addressing is performed by acoustically forming a column of mounds by driving all of the transducers in a column of droplet ejectors, while applying an electrode voltage to all of the electrodes of a row of droplet ejectors. Only the droplet ejectors associated with both an acoustically raised mound and with an applied electrode voltage will eject droplets.

FIG. 3 helps illustrate the inventive addressing of droplet ejectors. A plurality of droplet ejectors 50 (only 13 of which are shown) are organized into a number of rows 52 (only 4 of which are shown). The rows are arranged in an adjoining fashion such that corresponding droplet ejectors in adjacent rows are slightly offset. This slight offset creates slightly angled columns 54 of droplet ejectors. The transducers of the droplet ejectors in each column are electrically interconnected. Likewise, the electrodes of all of the droplet ejectors in each row are electrically interconnected. By driving each of the transducers of the droplet ejectors in a column, a column of mounds is formed.

By then applying an electrode voltage to each of the electrodes of the droplet ejectors in a row, the droplet ejector associated with both an acoustically raised mound and an applied electrode voltage ejects a droplet. Of course, those skilled in the applicable arts will appreciate that the above described organization of columns and rows can be interchanged.

Claims

1. A method of ejecting a droplet comprising the steps of:
   acoustically forming a mound (14) on the free surface (16) of a liquid (18); and
   electrostatically attracting (20) the liquid in the mound until a Rayleigh instability necks off the mound to form and eject a droplet (12).

2. A droplet ejector (10) for ejecting a droplet from the free surface of a liquid onto a recording medium (34), said droplet ejector comprising
   an ink well for holding a liquid (18) such that said liquid has a free surface(16);
   means (24,28,30) for acoustically forming a mound (14) on the free surface of the liquid; and
   means (20) for electrostatically attracting the liquid in said mound until a Rayleigh instability necks off the mound to form and eject a droplet (12) onto the recording medium (34).

3. The droplet ejector according to claim 2, wherein said means (20) for electrostatically attracting the liquid in said mound includes an electrode.

4. The droplet ejector according to claim 3, wherein said electrode (20) is disposed between said ink well and the recording medium (34).

5. The droplet ejector according to claim 4, wherein said electrode (20) includes a droplet opening (32).

6. The droplet ejector according to claim 3, wherein the recording medium (34) is disposed between said electrode (20) and said ink well.

7. A method of selectively ejecting droplets from a plurality of droplet ejectors (50) arranged in an array of rows (52) and columns (54), each of the droplet ejectors comprising an acoustic transducer and an electrode, the method comprising the steps of:
   acoustically forming at least one column (54) (or row) of mounds on the free surface of a liquid; and
   establishing electrostatically attractive forces from at least one row (52) (or column) of the electrodes such that a droplet is ejected from at least one of said acoustically raised mounds.

8. The method according to claim 7, wherein said electrostatically attractive forces are established when the apex of a mound (14) approaches its associated electrode (20).

9. A printer comprising
   a print head having of an ink well for holding ink (18) such that the ink has a free surface (16), said print head further having a plurality of droplet ejectors for ejecting droplets of the ink held in said ink well, each of said droplet ejectors including a transducer (24) for radiating acoustic energy toward said free surface such that a mound is formed on said free surface, each droplet ejector further including an electrode (20) disposed near its associated mound;
   means for driving the transducer of a first droplet ejector of said plurality of droplet ejectors so that a first mound (14) is formed on said free surface;
   means for applying a voltage to the electrode (20) of said first droplet ejector so that an electrostatically attractive force attracts said first mound such that a Rayleigh instability pinches off a droplet (12) from said first mound; and
   means for positioning a recording medium (34) such that said droplet is deposited on the recording medium.

10. The printer according to claim 9 including a control means for selecting said first droplet ejector from said plurality of droplet ejectors.

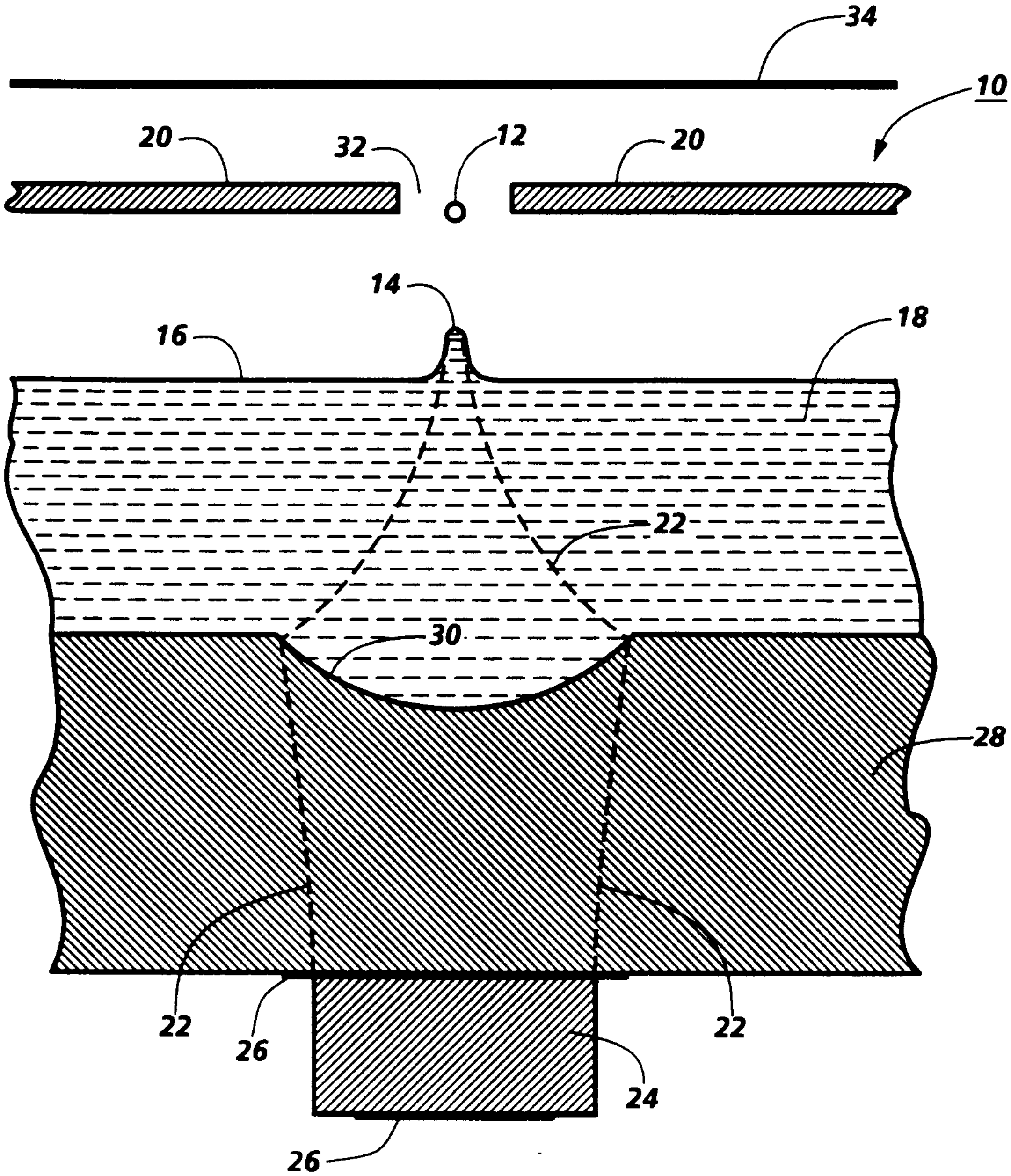

Fig. 1

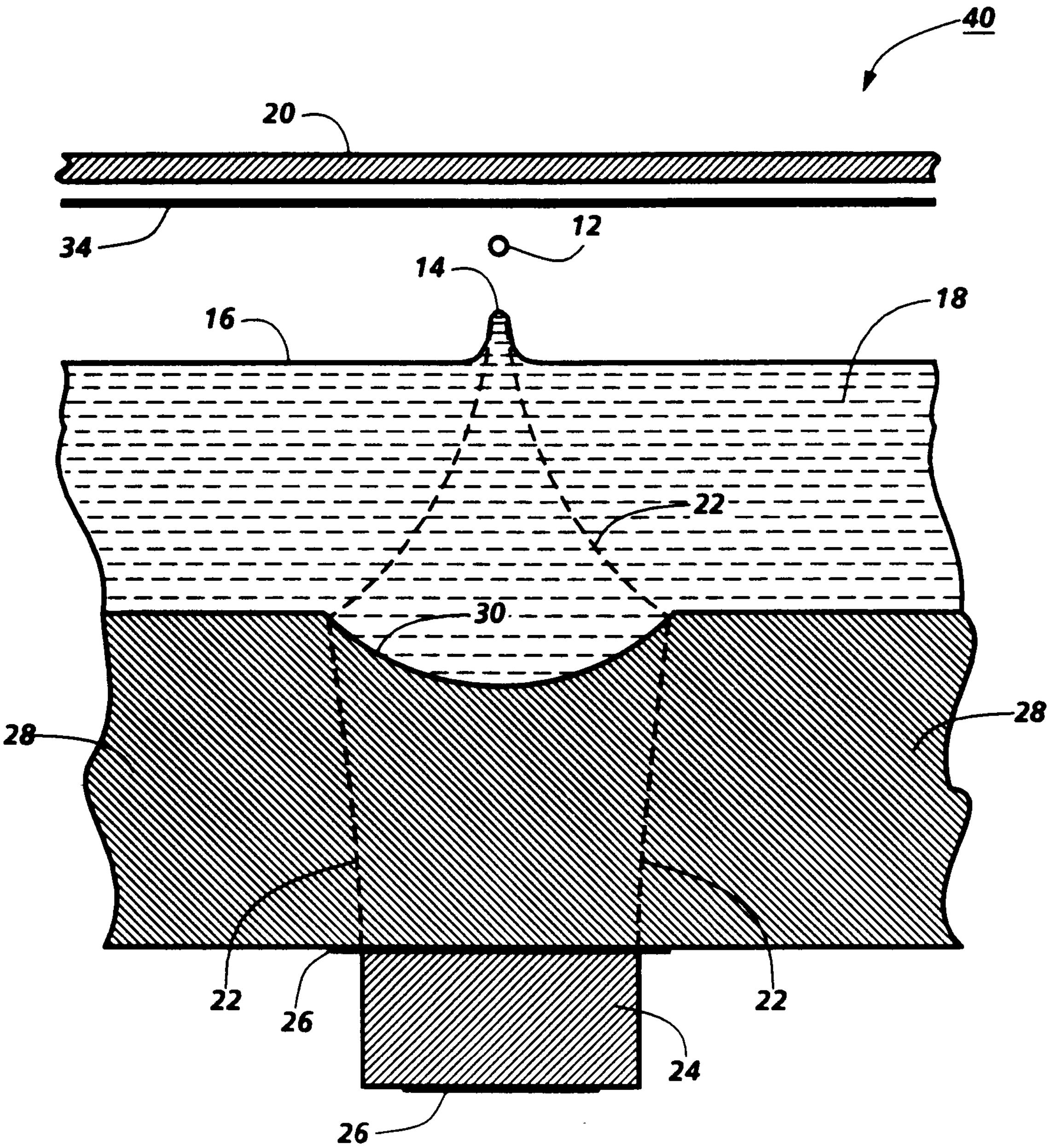

Fig. 2

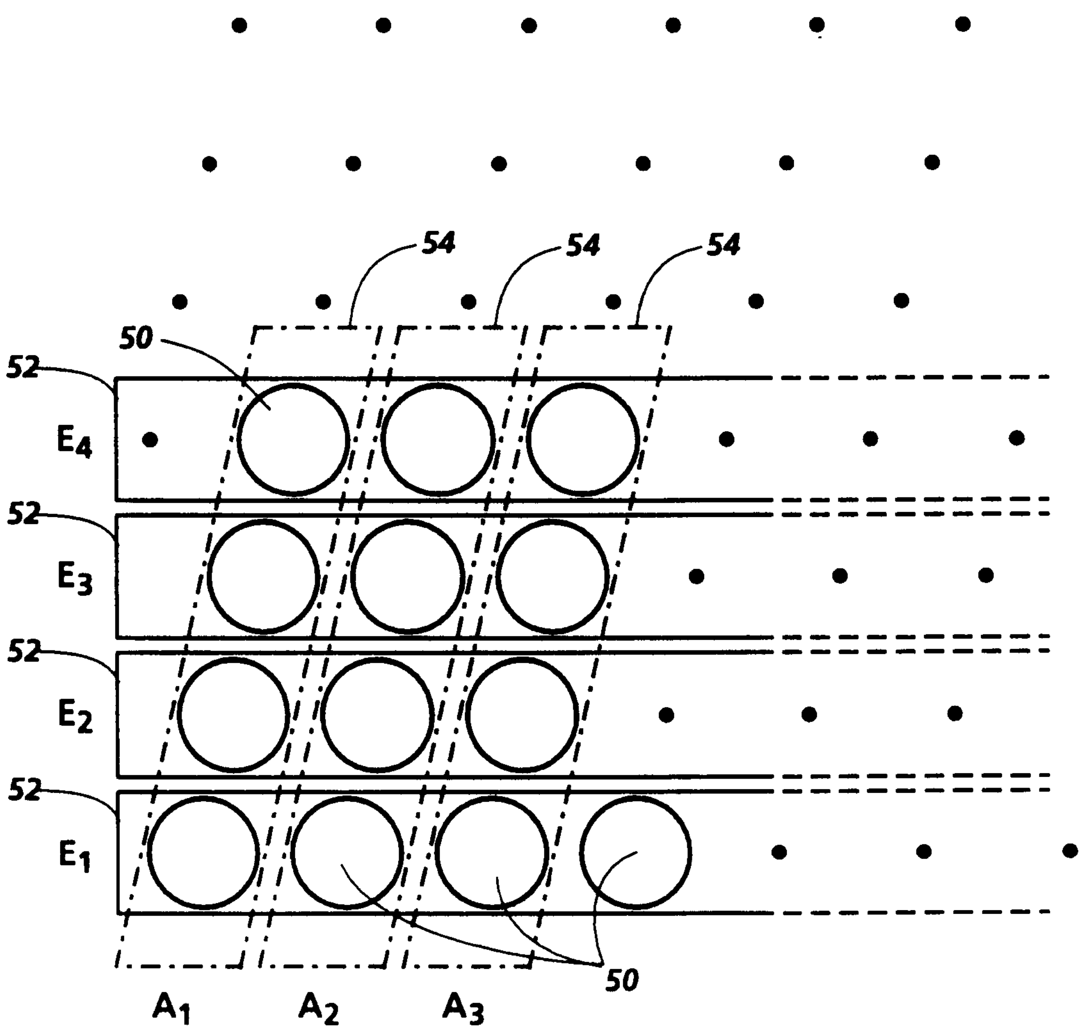

Fig. 3