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(54) Method for propelling droplets of a conductive liquid.

(57) A pulse of current of several hundreds of volts is established between two electrodes (1, 6) immersed in a resistive liquid (5). By the concentration of the current at the level of the end of the electrode (1), which it must be added is bonded onto an insulating support (2), a volume of liquid in contact with the end of this electrode (1) is vaporised, causing an abrupt drop in current. Because of the voltage of this pulse, which is of several hundreds of volts, a greater current re-establishes itself immediately across the volume of vaporised liquid, as a result of a sort of ionization of this vapour, causing superheating and energy sufficient to expel a droplet of liquid through an opening (4) provided in a membrane (3). In order to limit the energy of the superheating phase and control the size of the droplets, the current of the energising pulse is limited.

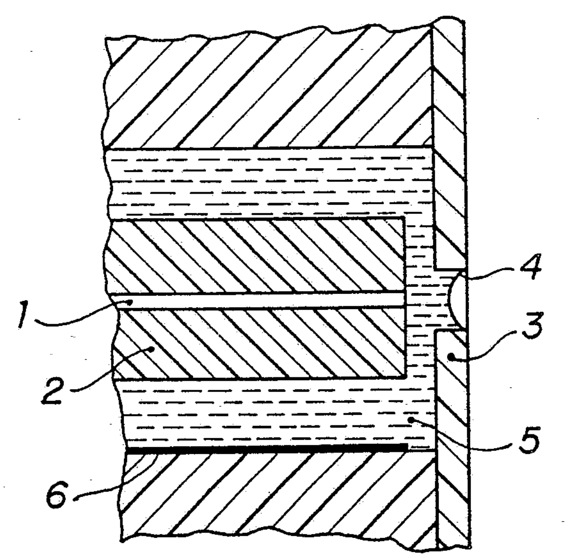

FIG. 1

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METHOD FOR PROPELLING DROPLETS OF A CONDUCTIVE LIQUID

The present invention relates to a method for propelling droplets of an electrically conductive liquid, according to which the end of a first electrode whose cross-section is approximately of the order of size of that of the droplets in disposed in this liquid, this end being flush with an insulated support surrounded by the said liquid a second electrode, a surface of which is substantially greater than that of the said end of the first electrode, is disposed in this liquid in contact with it, and these two electrodes are connected to the terminals of a pulse generator to cause resistive heating of the liquid in the immediate proximity of the said end, suitable for vaporising a quantity of the said liquid capable of producing a force able to propel a droplet of this liquid.

A structure capable of effecting such a method is described in European Patent Specification No. B1 0,106,802. Study of the manner of energising such a structure has shown that the results and the efficiency vary appreciably depending on the mode of energisation chosen. Thus, in French Patent Specification No. 2,092,577, it has been proposed to connect two electrodes submerged in liquid ink to a high voltage source to form a discharge circuit in such a manner as to create a spark which generates an over-pressure within the liquid, causing it to be ejected through an opening. Such a mode of energisation has disadvantages linked to the use of a high voltage source, the principal disadvantage arising however from the poor efficiency resulting from this mode of propulsion of liquid droplets.

The use of much lower voltages has shown that it is also possible to propel droplets of liquid by generating within the mass of liquid a force resulting from the vaporising of a volume of liquid in the neighbourhood of the end of an electrode aligned with the surface of an insulating support surrounded by the liquid, droplets of which are to be propelled. Detailed study of the phenomenon has shown, on the basis of measurements, that there exists a range of voltage for which an appropriate volume of liquid is vaporised. However, the vaporisation alone of this liquid in accordance with Ohms law is not sufficient to produce the propulsion energy necessary for the droplet. It has been remarked, however, that if the voltage is sufficient, as soon as the current tends to break-off, it is quickly re-established as a result of what may be interpreted as a sort of ionisation of the liquid vapour.

While this mode of propulsion shows itself to be effective and relatively efficient compared to other modes of propulsion of droplets on demand, used in particular in ink jet printing systems, poor reproducibility of that phase of the process of propulsion which may be termed "ionisation" has also been noticed, which shows as a great variation in the size of the droplets, from being equal to at least double, between the projection of two successive droplets. It is very evident that such a variation is not desirable, in particular when these droplets are intended to form characters in an ink jet printing system.

It has already been proposed in U.S. Patent Specification No. 4,746,937 to limit the energy in a very different ink jet system, in which the conductive ink is disposed in a long tube and fulfills the role of a heating resistance. In this ink jet, a volume of ink corresponding to several tens of times the volume of ink to be expelled is heated in such a way that if the heating conditions are kept constant, a stage is arrived at where the total volume of the tube is emptied as a result of constant increase in the temperature of the ink contained in this tube. It is for this reason that it has been proposed to control the duration of the ink preheating pulse in such a manner that it is inversely proportional to the initial temperature of the ink. This solution is of no great interest when the volume of ink heated is more or less equal to that expelled, such that the following volume of ink is more or less at ambient temperature. Thus this solution does not tackle the problem which concerns us.

It has also been proposed in U.S. Patent Specification No. 4,126,867 to limit the polarising voltage of the base of an amplifying transistor whose emitter is connected to a piezo-electric motor element but this does not advantageously tackle the problem which concerns us.

It is an object of the present invention to overcome at least in part the above-mentioned disadvantages.

Accordingly, the present invention has as a subject a method for propelling droplets of an electrically conductive liquid according to Claim 1.

Trials carried out using this method have shown that it enables the size of the propelled droplets to be controlled within limits, sufficient in particular for the needs of a printer.

The accompanying drawings illustrate, diagrammatically and by way of example, an embodiment and variants of a device for effecting the method which is a subject of the present invention, and also its energising circuit.

Figure 1 is a sectional view of a device for effecting this method.

Figures 2 and 3 are two voltage-current diagrams as a function of time between the electrodes.

Figure 4 is a schematic of an energising circuit for the device of Figure 1.

Figures 5 and 6 are two schematics of two variants of the circuit of Figure 4.

Figures 7 and 8 are two schematics of energising circuits for a series of drive electrodes.

The device illustrated in Figure 1 corresponds to that which is described and illustrated in European Patent Specification No. B1 0,106,802, which may be advantageously referred to for further details. This device comprises a first electrode 1 formed by a thin wire of a metal which is a good conductor of electricity and is corrosion resistant, bonded onto an insulating support 2. The end of this electrode 1 is flush with the surface of this support 2. A membrane 3, which may be metallic, is pierced by an opening 4, disposed co-axially with the electrode 1, and serving for the projection of droplets of a liquid 5, which fills the space between the membrane 3 and the insulating support 2, this space forming the reservoir for the liquid. A second electrode 6, whose surface in contact with the liquid is appreciably greater than that of the end of the electrode 1, is disposed somewhere in the volume of liquid 5.

By way of example, tests have been carried out with a membrane 3 40 µm to 50 µm thick, the opening 4 having a diameter of 80 µm to 100 µm, the membrane 3 being 40 µm from the support 2, and the electrode 1 being formed by a wire of stainless steel or platinum 20 µm to 25 µm diameter. Copper is also of interest as a metal for the electrode, in particular in regard to its resistance to electro-erosion. Other dimensions and different materials have been used and also the electrode 1 has been placed at a positive or negative polarity, thus changing the direction of the current. Taking into consideration the fact that the conductive ink behaves as an electrolyte, if the polarity of the electrode 1 is positive, it receives oxygen and is thus subjected to a high risk of corrosion. In the opposite case, the electrode 1 becomes the cathode, and it receives hydrogen or metal. These tests have been carried out with inks whose resistivity is between 40 ohm-cm and 560 ohm-cm, and the supply voltage at the electrodes was between 100 and 700 volts.

When the voltage is relatively low, that is to say in the above-mentioned conditions, of the order of 100 V, a reduction in the current is noticed, as is shown by the curve of the diagram of Figure 2b. This drop in the current should correspond to the vaporisation of the ink in contact with the end of the electrode 1. The energy produced by this purely resistive heating phase is insufficient to cause the ejection of a droplet of the liquid. Furthermore, the change of phase of the liquid in proximity to the end of the electrode 1 explains the fall-off in current measured.

When the supply voltage at the electrodes 1 and 6 is increased, after a fall-off in the current (Figure 3b), a sudden increase in the current is seen to appear, accompanied by a more or less stable voltage (Figure 3a) tending to reduce. This phenomenon, which was observed in a consistent manner, does not obey in any way Ohms law and may be likened to a current resulting from a sort of ionisation of the liquid vapour. The observations taken during numerous tests have enabled it to be confirmed that this second phase, which causes a superheating as a result of the establishment of an ionic current, seems absolutely indispensable for obtaining the energy capable of causing the projection of a droplet of liquid.

Amongst all the many parameters intervening in the process of projection of droplets, the superheating phase obtained on account of an increase in current is that which influences to the greatest extent the result obtained. However, this current is strongly dependent on the level of ionisation, such that the corresponding energy may be very variable. Consequently, the formation and the dimension of the droplets may also vary in the same proportions, which constitutes an important disadvantage in this method of projection of droplets, consistency obviously being a quality factor, in particular in the context of a printing process.

It is precisely the solving of this problem that the invention has an object, by limiting the current and as a consequence the energy during this second phase of the process of projection of droplets, so as to stabilise the formation of the droplets, reduce their size and maintain consistency of size.

Figure 4 illustrates the circuit of the electrical pulse generator used to produce the short voltage pulses of a duration of 5 to 10 microseconds and at a voltage preferably between 400 and 600 volts. The resistivity of the ink is chosen preferably between 400 and 800 ohm-cm. Below this limit, the electrochemical current would be increased and as a consequence the production of gas bubbles, while above this limit, the voltage of the electrical pulses would be increased.

To produce the pulses from a low voltage source of 10 to 20 volts, this circuit comprises a step-up transformer TR in which the ratio between the secondary S400 and the primary P10 is here 40, that is, 400 turns for the secondary and 10 for the primary.

The primary P10 of this transformer is supplied with pulses by a generator G, which delivers pulses of the desired duration, here of 5 to 10 µs, to the base of a field effect transistor T1.

With a view to making the transformer work with symmetrical pulses in regard to the product of voltage x time, the supply circuit for the primary P10 of the transformer TR has three diodes in series, D_1, D_2, D_3, with a resistance R1200 and a capacitor C2µF. These diodes in series with the resistance R1200 produce a polarisation of about 1.5V stored in the capacitor C2µF. When a pulse from the generator G amplified by the transistor T1 terminates, the capacitor C2µF discharges with a current of opposite direction directed in the direction of the arrow CD, which passes through the resistance R120 and repolarises the transformer TR for the next pulse from the generator G.

To make the current at the terminals of the secondary S400 independent of the charge in the ionised liquid vapour, which may be very variable, as previously explained, a current limiting circuit is associated with the secondary S400.

The part of this circuit comprising a resistance R1M in series with a resistance R5K in parallel with a Zener diode is connected to the base of a transistor T_2. The electrodes 1 and 6 of Figure 1 are connected respectively to the points a and b of the circuit of Figure 4, in such a way that the electrode 1 is negative with respect to the ink and the current I goes from the ink towards the electrode 1 in the direction of the arrow of Figure 4. This enables electrochemical corrosion of the electrode 1 to be avoided. Because of the Zener diode, the polarising voltage e_o of the transistor T_2 is maintained constant. Its emitter is thus at a potential e_o' corresponding to the voltage e_o less the voltage of the transistor, which is here 0.2V. The voltage e_o corresponds to:

$e_o' = R_3 \cdot I$

then,

$$I = \frac{e_o'}{R_3} = \frac{e_o - 0.2}{R_3}$$

By suitably choosing the value of e_o, which is given by the Zener diode DZ, and the value of the resistance R_3, a constant current Io is obtained. For example with:

e_o = 1.2 volts

R_3 = 100 ohms

I_o = 10 mA

the same current, 10 mA, may be obtained with e_o = 10.2 volts and R3 = 1000 ohms. Because of this limitation of the supply current to the electrodes 1 and 6, the energy W in the discharge is limited to a fixed value:

$$W = \int_0^T vi\,dt$$

v = ionising voltage -3 V_o

$$W = V_o \int_0^T i\,dt$$

If precise definition of the energy is desired, a circuit supplying, a priori, a voltage greater than V_o must be used, for example V_o+50 or 100 volts, and the circuit described above placed in series with the source giving this voltage, limiting the current to a fixed value I_o, such that

$W = V_o I_o T$

Another solution giving a less precise result but one which may be sufficient, would consist of using a series impedance, for example a resistance equal to the resistance of the electrode 1.

The circuit of Figure 4 was tested with success by limiting the value of the current I_o to 30 mA. Accordingly comparative tests with and without current limitation were carried out. On the one hand, the energy of the phase 2 of superheating producting the projection of the droplets was measured and the diameter of the droplets obtained was also measured. The tests were carried out with a device comprising an electrode 1 ot 12 µm diameter, of platimun, and having an opening 4 of 80 µm diameter and 40 µm length. The table below indicates the results obtained in the two cases.

	Superheating Energy (microjoules)	Dimension of droplets (µm)
With current limitation	30	100 - 120
Without current limitation	30 - 80	100 - 200

The results show clearly that the limitation of super-heating energy corresponding to the second phase of the process of projection of the droplets enables good consistency in the size of the droplets to be obtained, while without this limitation, this size varies from being equal to double. It is evident, in particular in the case of a demand ink jet on a printing device, that this control of the size of the droplets constitutes an essential quality factor. Of course, a number of other parameters intervene in the process of formation of the droplets. However, these parameters do not have a marked influence on the consistency of the size of the droplets. As a consequence, these other parameters intervene above all in the initial choice at the time of conception of the projection device. On the other hand, and whatever the parameters adopted may be, the instability of the process of projection intervenes and is inherent in this process, as long as the energy of the super-heating phase of the liquid vapour is not limited. It hus follows that in the context of the droplet propulsion process described, this limitation is a determining element for consistency, inherent in the fact that only the superheating phase of the liquid vapour is capable of producing sufficient energy to project the droplets, but that the current in this medium in the vapour phase is extremely variable from one moment to another, generating energy levels liable to vary in an approximate ratio of 1 to 3.

Obviously other means exist for limiting or defining the energy during the drive pulse for a droplet. Thus, an intermediate energy storage element such as a capacitor or an inductance may be used.

A circuit enabling the energy delivered to be limited or defined by means of a capacitor C is illustrated in Figure 5. A resistance R is chosen so that the capacitor C is charged slowly to a selected voltage V greater than the ionisation voltage V_o. While the transistor T conducts, the capacitor C discharges into the conductive liquid to be propelled between the electrodes 1 and 6, at a current level I, until the moment when the voltage becomes less than the ionisation voltage V_o. At that moment, the transistor T ceases to conduct and the current I is interrupted. The energy delivered is thus equal to

$1/2\ C\ (V^2 - V_o^2)$

Figure 6 illustrates the case of a circuit using an inductance L to limit the energy delivered. It is to be noted however that this second solution is more difficult and more expensive than the preceding, as it requires a very great inductance L of the order of 100 mhenry while the circuit of Figure 5 only requires a very small capacitor C of the order of 100 picofarad.

Between the drive pulses for the droplets, the transistor T conducts and a current $I = V/R$ is established in the inductance L. To produce a pulse capable of propelling a droplet of liquid through the opening 4, the transistor T is then cut-off, causing at the point A of the circuit an increase in voltage sufficient to re-establish the current across the vaporised liquid because of the ionisation. The discharge current of the inductance L continues until all the stored energy disappears. The energy supplied thus corresponds to: $-\ 1/2\ L\ I^2$.

The process according to the invention has been described in relation to the energising of a single electrode 1 for propelling droplets. In practice, the membrane will comprise several openings 4 side by side, and the insulating support several electrodes 1.

By definition, the ink is equipotential with respect to the electrodes 1 and 6. Preferably, the membrane 5 is electrically conductive, being for example formed by a sheet of copper which also serves as a counter-electrode 6. This arrangement enables interference between neighbouring propelling devices to be avoided, which are spaced in this example at 250 µm from axis to axis, and in particular it enables obstruction of the passage of current in the case of formation of bubbles on an electrode 1 to be avoided. By locating the counter-electrode opposite the electrodes 1, these bubbles do not obstruct the flow of the current between the neighbouring electrodes and the counter-electrode.

There exists in this case two possibilities for selectively energising the electrodes 1, either by using a common source of high voltage pulses for a series of electrodes, or by using one pulse source per electrode.

In the schematic of Figure 7, there may be noted the insulating support 2, the electrodes 1 to 1n, and the membrane 3 with the openings 4 disposed opposite the electrodes 1 to 1_n. On the actual electrical schematic, there is a high voltage source HT with the primary P10 and the secondary S400 of the transformer TR supplying the high voltage pulses of ≈ 400 volts. Each electrode 1 to 1_n is associated with a selector comprising a selection transistor TS_1 to TS_n whose base is selectively polarised by the logic of the printer (not shown) by voltage signals E_1 to E_n. These transistors are provided with current limitation by virtue of the resistance of 220 ohms for example, placed in series with the emitter. The current is thus limited to

$(E_i - V_{be}) / 220$

$(5 - 1) / 220 \approx 18mA$

(V_{be} : base-emitter voltage of the transistor).

The selectors thus play a double role, actual selection and limitation of current, and therefore of energy.

The ink and the membrane 3 must be at a positive potential with respect to the electrodes 1 to 1n to ensure that the direction of the current is such that it enters these electrodes from the ink in such a manner that the potential of ≈ 400 volts is applied to the membrane 3 while the electrode selectors are con nected to a 0 V reference potential.

In the variant of Figure 8, each electrode 1 to 1n is energised by the secondary S400 of an independent transformer supplying a pulse of ≈ 400 volts to the electrode. The reference point of each secondary is connected to a 0 volt potential, as is the membrane 3 which plays the role of counter-electrode.

Each pulse carries the potential of the electrode or the electrodes selected at -HT (≈ 400 volts) to ensure the direction of the current from the ink to the electrode, the counter electrode being at the 0 volt potential.

The selection transistors TS_1 to TS_n are arranged in series with the primary P10 of each transformer. The base of each transistor is selectively polarised by the logic of the printer by voltage signals E_1 to E_n. These transistors are provided with current limitation by virtue of the resistance of 1.5 ohms in series with the emitter. In this way, the current at the secondary S400 and as a consequence that on the electrode is likewise limited. The leakage self-inductance of the transformers also produces a dynamic limitation of the electrode current.

Claims

1. A method for propelling droplets of an electrically conductive liquid, according to which the end of at least a first electrode whose cross-section is approximately of the order of size of the droplets is disposed in this liquid, this end being flush with an insulating support surrounded by the said liquid, a second electrode a surface of which is substantially greater than that of the said end of the first electrode is disposed in this liquid in contact with it, and these two electrodes are connected to the terminals of a pulse generator for causing resistive heating of the liquid in the immediate proximity of the said end, suitable for vaporising a quantity of the said liquid capable of producing a force able to propel a droplet of this liquid, characterised by the fact that once the said quantity of liquid has been vaporised, tending to cause a break in the current, the voltage is fixed at a value capable of ionizing the vapour of the said quantity of vaporized liquid and simultaneously the current crossing this quantity of vaporised liquid is limited below a predetermined threshold, to produce within the mass of this quantity a controlled superheating energy.

2. A method according to Claim 1, characterised by the fact that the voltage of the energising pulse is chosen above the ionizing voltage of the vapour of the said liquid to automatically bring about this ionization after the drop in the current resulting from the vaporisation of the said quantity of liquid.

3. A method according to Claim 1, characterised by the fact that in order to limit the current of the energising pulse, a constant voltage is set on the base of a transistor and a resistance is placed in series with its emitter, whose value is chosen so that the current appearing at the collector and which corresponds to the quotient of the voltage of the emitter by this resistance, does not exceed to predetermined value.

4. A method according to Claim 3, characterised by the fact that the base of the transistor is connected between two resistances in series connecting the two terminals of the pulse source, and that a Zener diode is disposed in parallel with the resistance, which goes from the base of the transistor to the negative terminal of the said source.

5. A method according to Claim 1, characterised by the fact that in order to limit the energy of the energising pulse, a capacitor is disposed between the first and the second electrode, the discharge of this

capacitor is controlled by means of a transistor whose conduction threshold is fixed above the ionization voltage of the said vapour and the charging of the capacitor is controlled by means of a resistance.

6. A method according to Claim 1, characterised by the fact that in order to limit the energy of the energising pulse, an inductance is placed in series with a transistor disposed between the two electrodes, this transistor is closed to charge the inductance between the energising pulses, then, at the moment of a pulse, this transistor is cut-off to increase the voltage at the output of the inductance to a value greater than the ionization voltage of the said quantity of vaporised liquid, permitting the current to re-establish itself and the inductance to discharge.

7. A method according to Claim 1 characterized by the fact that the direction of flow of the current is chosen in such a manner that it flows from the said second electrode towards the said first electrode across the said electrically conductive liquid.

8. A method according to Claim 3, characterised by the fact that in the electrically conductive liquid a plurality of the said first electrodes are disposed and that these electrodes are energised by high voltage pulses from a common source on the one hand and on the other hand by control signals caused to appear at the base of a selection transistor provided for current limitation with the said common source.

9. A method according to Claim 3, characterised by the fact that in the electrically conductive liquid a plurality of the said first electrodes are disposed and that each is energised with high voltage pulses by the secondary of a transformer, that a selection transistor is provided in series with each primary, on the base of which the control signals are caused to appear, and that each of these transistors is provided for current limi tation.

10. A method according to one of Claims 8 and 9, characterised by the fact that an electrically conductive membrane is disposed opposite the respective ends of the said first electrodes disposed in the electrically conductive liquid, that this membrane is pierced by an opening opposite each of the said ends, and that this membrane is connected to one of the terminals of the said pulse generator.

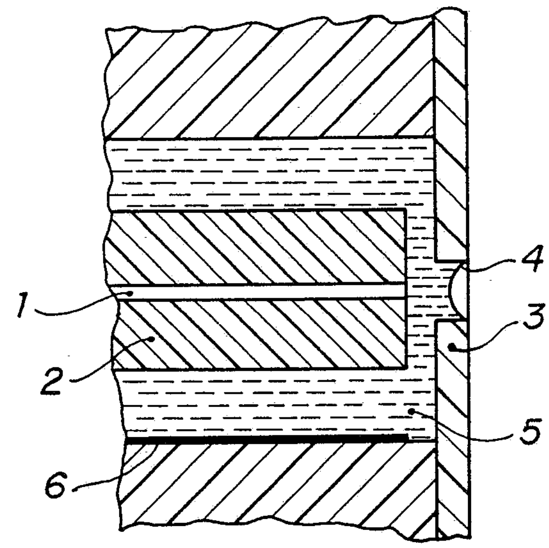

FIG. 1

FIG. 2a

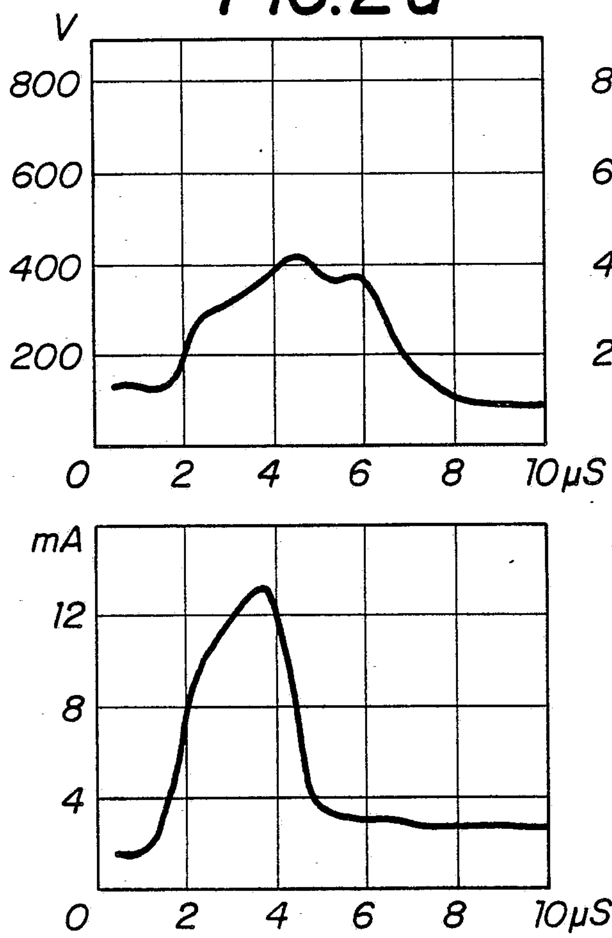

FIG. 2b

FIG. 3a

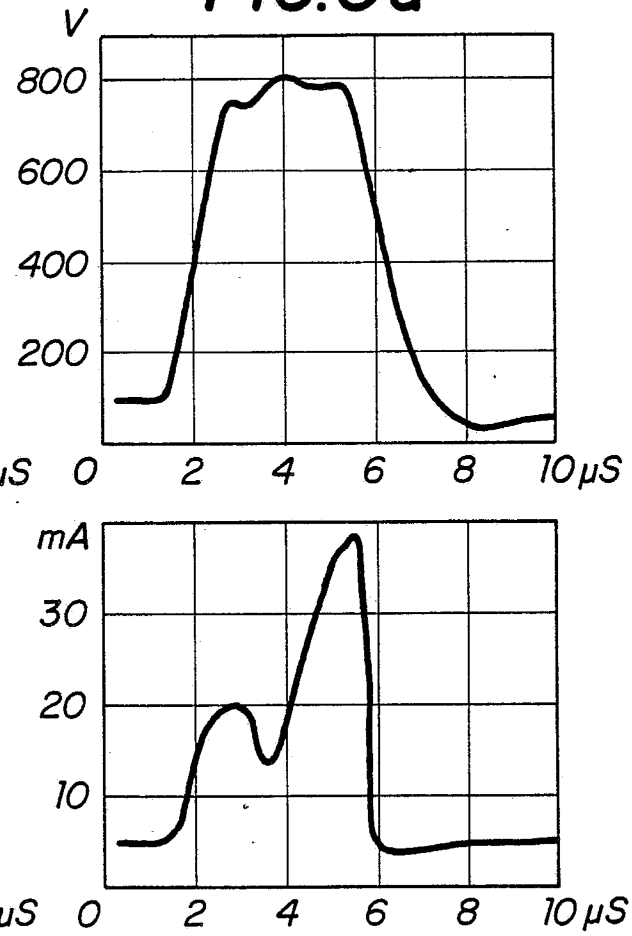

FIG. 3b

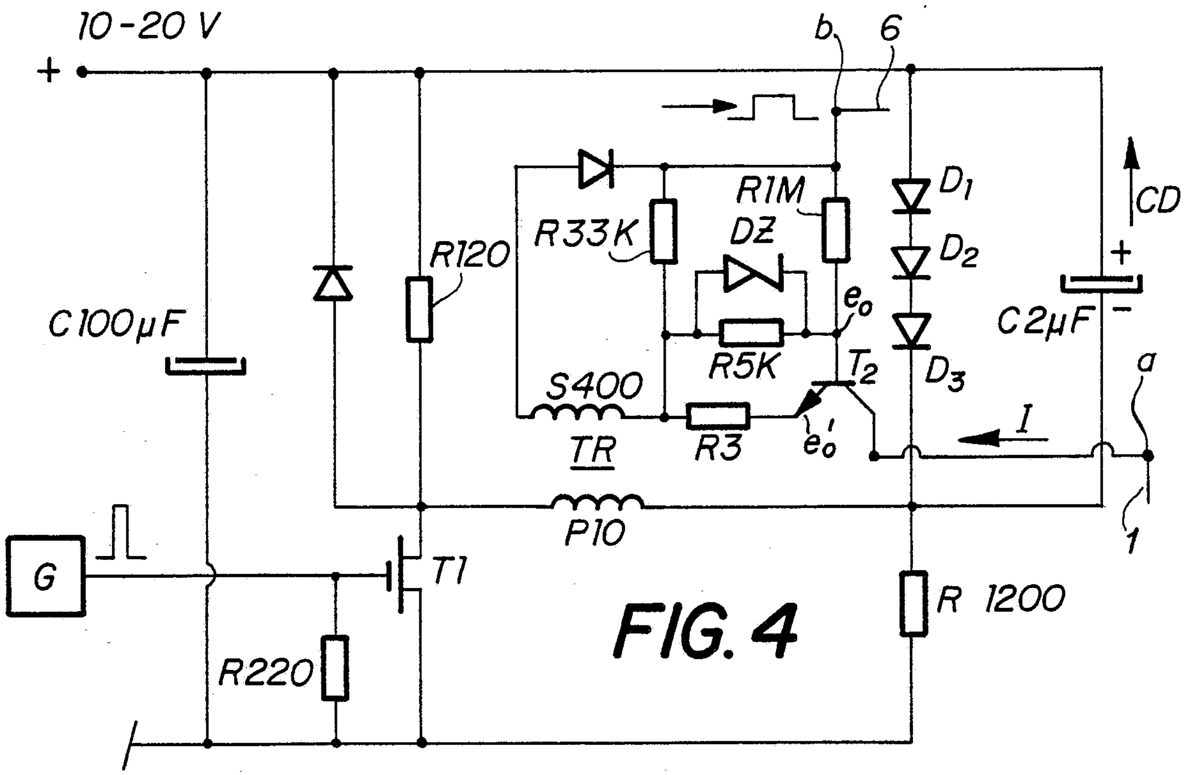

FIG. 4

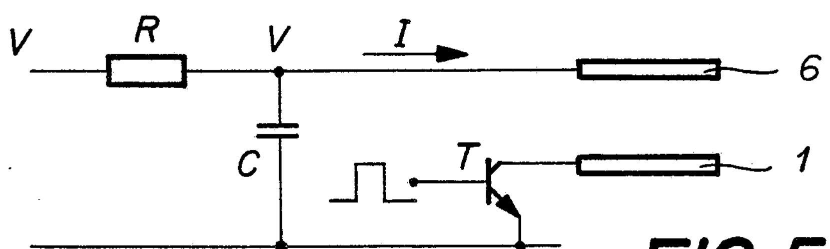

FIG. 5

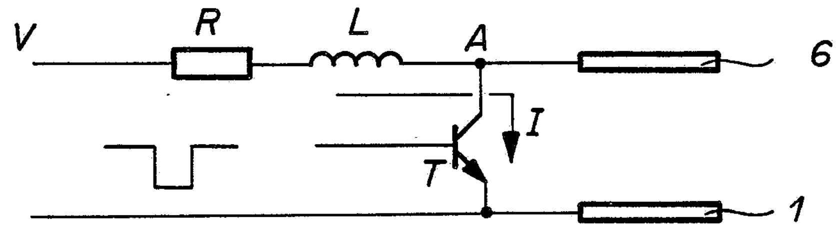

FIG. 6

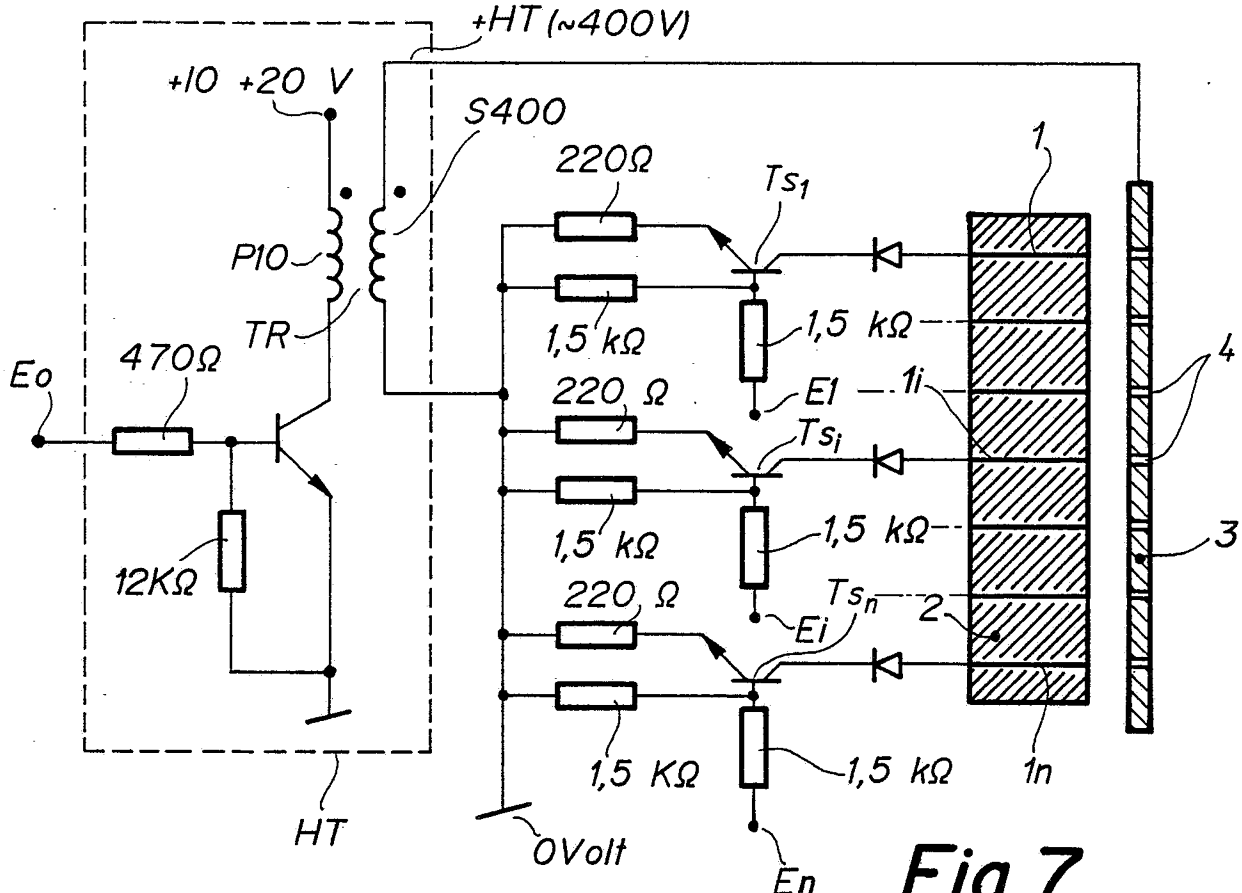
+HT(~400V)
+10 +20 V
S400
220Ω
Ts1
1
P10
1,5 kΩ
1,5 kΩ
TR
470Ω
4
Eo
220 Ω
E1
1i
Tsi
1,5 kΩ
1,5 kΩ
3
12KΩ
220 Ω
Tsn
2
Ei
1,5 KΩ
1,5 kΩ
1n
HT
0Volt
En

Fig.7

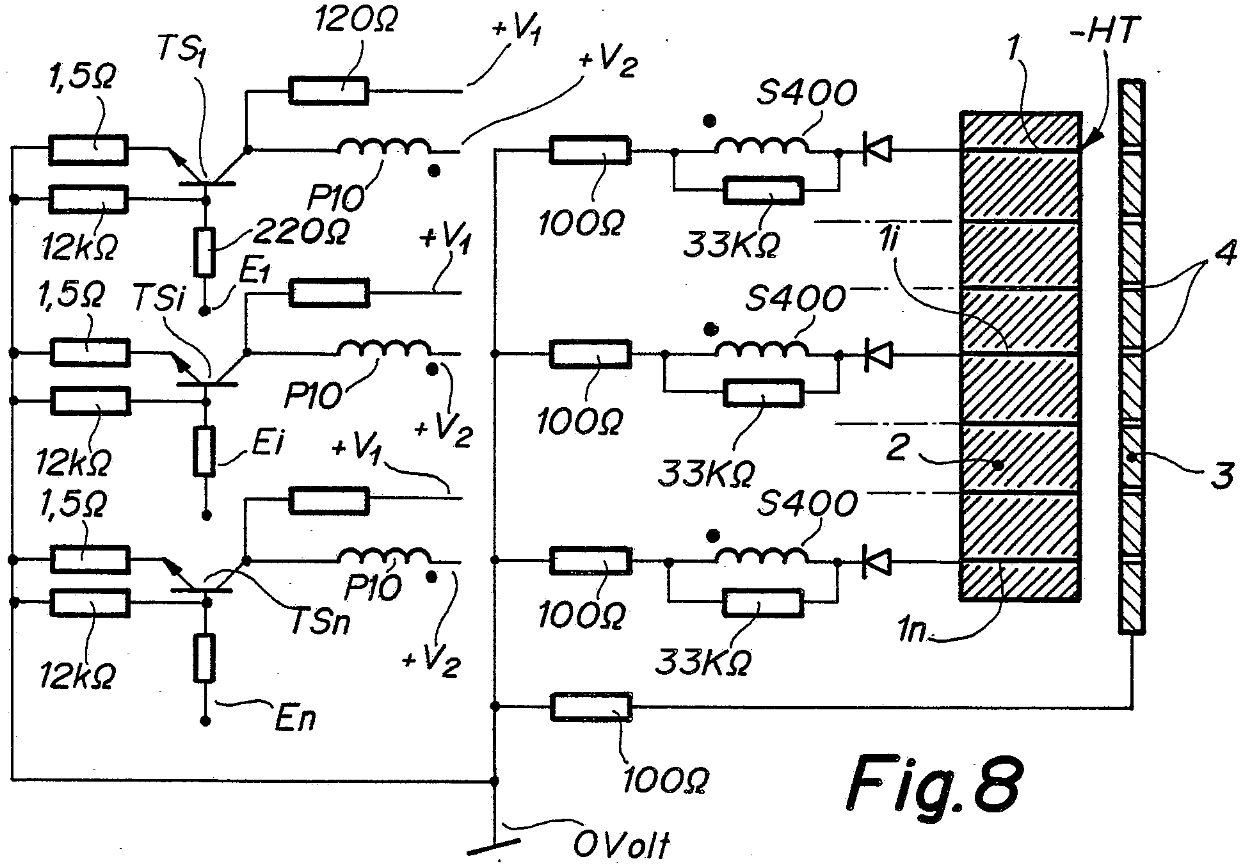
120Ω
+V1
TS1
+V2
-HT
1,5Ω
1
S400
P10
12kΩ
220Ω
100Ω
33KΩ
+V1
1i
4
1,5Ω
TSi
E1
S400
P10
+V2
12kΩ
Ei
100Ω
33KΩ
2
3
+V1
1,5Ω
S400
P10
TSn
100Ω
12kΩ
+V2
33KΩ
1n
En
100Ω
0Volt

Fig.8

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 89 81 0741

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
D,A	US-A-4746937 (REALIS LUC ET AL) * abstract; claims 1-10; figures 3, 6, 7 * * column 1, lines 32 - 40 * * column 2, line 43 - column 3, line 12 * * column 3, lines 2 - 13 * ---	1-4, 6	B41J2/06
D,A	US-A-4126867 (STEVENSON, RICHARD G. JR.) * column 6, lines 16 - 43; figures 3-5 * ---	3, 4	
A,D	EP-A-106802 (BATTELLE MEMORIAL INSTITUTE) -----		

TECHNICAL FIELDS SEARCHED (Int. Cl.5)

B41J

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	12 DECEMBER 1989	ROBERTS N.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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L : document cited for other reasons

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