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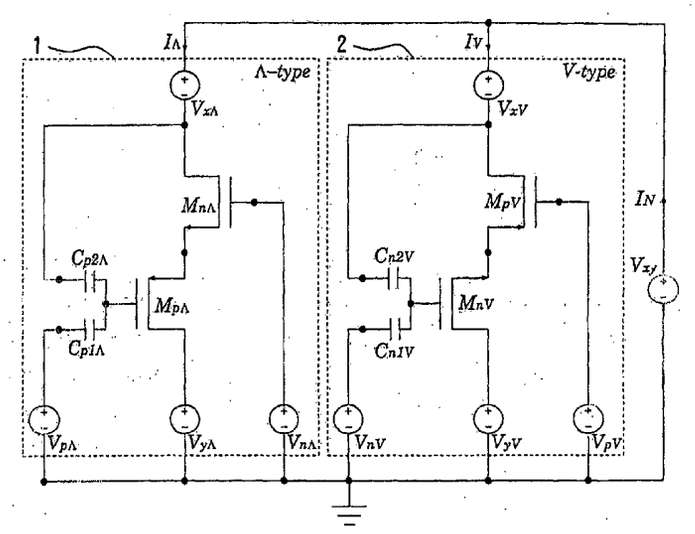
(54) NONLINEAR RESISTOR CIRCUIT USING FLOATING GATE MOSFETS

(57) An N-shaped nonlinear resistor circuit using floating gate MOSFETs to realize various N-shaped characteristics that can be approximated by piecewise linear functions of third to seventh orders and further to realize N-shaped V-I characteristics that can variously change those characteristics by use of external voltages.

A Λ-type nonlinear resistor circuit (1) and a V-type nonlinear resistor circuit (2) using multi-input floating gate MOSFETs are connected in parallel, and the currents of the Λ-type and V-type nonlinear resistor circuits are added together, thereby providing various N-shaped voltage-current characteristics.

F I G. 1



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Description

Technical Field

[0001] The present invention relates to a nonlinear resistor circuit using floating gate MOSFETs, and more particularly, to a circuit which realizes various N-shaped voltage-current characteristics.

Background Art

[0002] Conventionally, reference documents on the above-mentioned field include the following disclosures.

Reference document (1): Japanese Patent no. 3,007,327: Y. Horio, K. Watarai, and K. Aihara, "Nonlinear resistor circuits using capacitively coupled multi-input MOSFETs," IEICE Trans. Fundamentals, vol. E82-A, no. 9, pp. 1926-1936, 1999.

Reference Document (2): K. Matsuda, Y. Horio, and K. Aihara, "A simulated LC oscillator using multi-input floating-gate MOSFETs," in Proc. IEEE Int. Symp. on Circuits and Syst,. vol. III, pp. 763-766, 2001.

Reference document (3): Kinya Matsuda, Tomonori Amano, Yoshihiko Horio, and Kazuyuki Aihara, "LC oscillator using capacitively coupled multi-input MOSFETs," Proceedings of 13th Karuizawa workshop on circuits and systems, the Institute of Electronics, Information and Communication Engineers (IEICE), pp. 35-40, 2000.

Reference Document (4): Kinya Matsuda, Yoshihiko Horio, and Kazuyuki Aihara, "Method for high-Q active inductor circuit," Technical Report of IEICE, vol. NLP 2001-39, pp. 37-41, 2001.

Reference document (5): T. Matsumoto, L. O. Chua, and M. Komuro, "The double scroll," IEEE Trans. on Circuits and Syst., vol. CAS-32, no. 8, pp. 798-817, 1985.

Reference document (6) : J. M. Cruz and L. O. Chua, "A CMOS IC nonlinear resistor for Chua's circuit," IEEE Trans. on Circuit and Syst., 1, vol. 39, no. 12, pp. 985-995, 1992.

[0003] The inventor of the.present invention suggests a conventional nonlinear resistor circuit using the multi-input floating gate MOSFET as one of circuits having a negative voltage-current (V-I) characteristic area (in reference document (1)), and it is applied to an inductor simulation or a sine wave oscillator circuit (in reference documents (2) to (4)). In the circuits, Λ-shaped and V-shaped nonlinear resistor characteristics are realized and further the characteristics are changed by external voltages.

[0004] In addition, an N-shaped nonlinear resistor characteristic has the negative resistor area in the center and therefore is widely used for an oscillating circuit or neuron device. In particular, the N-shaped nonlinear resistor characteristic approximates to the piecewise linear characteristics of third to fifth orders can form a sine wave oscillator or a chaos generating circuit by combining L and C (in reference documents (5) and (6)).

Disclosure of Invention

[0005] In consideration of the above-mentioned problems, it is one object of the present invention to provide a nonlinear resistor circuit using floating gate MOSFETs for realizing N-shaped V-I characteristics, which enables various N-shaped characteristics approximate to piecewise linear functions of third to seventh orders by applying the nonlinear resistor circuit using the multi-input floating gate MOSFETs and which variously changes the characteristics by the external voltages.

[0006] In order to accomplish the above-mentioned object,

(1) there is provided a nonlinear resistor circuit using floating gate MOSFETs, wherein a Λ-shaped nonlinear resistor circuit using a multi-input floating gate MOSFET and a V-shaped nonlinear resistor circuit using a multi-input floating gate MOSFET are connected in parallel therewith and current of the Λ-shaped nonlinear resistor circuit and current of the V-shaped nonlinear resistor circuit are added, thus to combine various N-shaped voltage-current characteristics.

(2) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (1), the N-shaped voltage-current characteristic is continuously changed.

(3) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (2), the voltage-current characteristics approximate to the piecewise linear characteristics of third to seventh orders are realized.

(4) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), negative resistor portions in the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and in the voltage-current characteristic of the V-shaped nonlinear resistor circuit are linear as much as possible, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-

shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between an input terminal of the Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of the V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the characteristic of the third order.

(5) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), negative resistor portions in the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and in the voltage-current characteristic of the V-shaped nonlinear resistor circuit are linear as much as possible, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of the Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of the V-shaped nonlinear resistor circuit, thus to combine the characteristic of the third order.

(6) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), an inclination of a negative portion of the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of the V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of the V-shaped nonlinear resistor circuit is moved in parallel in the left and right directions by a voltage between an input terminal of the Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of the V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the fourth order characteristic.

(7) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), an inclination of a negative portion of the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of the V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of the V-shaped nonlinear resistor circuit is moved in parallel in the left and right directions by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of the Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of the V-shaped nonlinear resistor circuit, thus to combine the fourth order characteristic.

(8) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), inclinations of negative portions of both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between an input terminal of the Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of the V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the fifth order characteristic.

(9) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), inclinations of negative portions of both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of the Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of the V-shaped nonlinear resistor circuit, thus to combine the fifth order characteristic.

(10) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), an inclination of a negative portion of the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of the V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between an input terminal of the Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of the V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the sixth order characteristic.

(11) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), an inclination of a negative portion of the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of the V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of the Λ-shaped nonlinear resistor

circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of the V-shaped nonlinear resistor circuit, thus to combine the sixth order characteristic.

(12) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), inclinations of negative portions of both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between an input terminal of the Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of the V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the seventh order characteristic.

(13) In the nonlinear resistor circuit using the floating gate MOSFETs according to the description (3), inclinations of negative portions of both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of the Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of the V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of the Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of the V-shaped nonlinear resistor circuit, thus to combine the seventh order characteristic.

Brief Description of the Drawings

[0007]

Fig. 1 is a diagram showing an N-shaped nonlinear resistor circuit using floating gate MOSFETs according to the present invention;

Fig. 2 are diagrams showing various V_{xy}-I_A characteristics (value simulations) in Fig. 1;

Fig. 3 are diagrams showing various V_{xy}-$I_{\overline{V}}$ characteristics (value simulations) in Fig. 1;

Fig. 4 are diagrams showing V-I characteristics approximate to a piecewise linearity according to the present invention;

Fig. 5 is a principle diagram of the combination of the N shaped V-I characteristics of the third order according to the present invention;

Fig. 6 is a diagram showing examples (numerical simulations) of nonlinear resistor characteristics which are approximate to the piecewise linearity of the third order according to the present invention;

Fig. 7 is a diagram showing an example of the fifth order nonlinear resistor characteristic (in which the voltage coordinate of a break point is fixed and inclinations m_0 and m_1 are changed) according to the present invention;

Fig. 8 is a diagram showing an example of the fifth order nonlinear resistor characteristic (in which the inclinations m_0 and m_1 are fixed, break points B_{P2-} and B_{P2+} are fixed, and break points B_{P1-} and B_{P1+} are changed) according to the present invention;

Fig. 9 is a diagram showing an example of the fifth order nonlinear resistor characteristic (in which the inclinations m_0 and m_1 are fixed, the break points B_{P1-} and B_{P1+} are fixed, and the break points B_{P2-} and B_{P2+} are changed) according to the present invention;

Fig. 10 is a diagram showing an example of the fourth order nonlinear resistor characteristic according to the present invention;

Fig. 11 is a diagram showing an example of the sixth order nonlinear resistor characteristic according to the present invention;

Fig. 12 is a diagram showing an example of the seventh order nonlinear resistor characteristic according to the present invention;

Fig. 13 are diagrams (No. 1) showing circuit simulation results using HSPICE;

Fig. 14 are diagrams (No. 2) showing the circuit simulation results using HSPICE;

Fig. 15 is a diagram showing an experimental circuit using discrete parts;

Fig. 16 is a diagram showing the third order V_{xy}-I_N characteristic obtained by the experiment using the discrete parts;

Fig. 17 is a diagram showing the fourth order V_{xy}-I_N characteristic obtained by the experiment using the discrete parts;

Fig. 18 is a diagram showing the fifth order V_{xy}-I_N characteristic obtained by the experiment using the discrete parts;

Fig. 19 is a diagram showing the sixth order V_{xy}-I_N characteristic obtained by the experiment using the discrete parts;

Fig. 20 is a diagram showing the seventh order V_{xy}-I_N characteristic obtained by the experiment using the discrete

parts;
Fig. 21 is a micro-photograph as a substitute drawing showing an IC chip including the circuit shown in Fig. 15;
Fig. 22 is a diagram (No. 1) showing a V_{xy}-I_N characteristic measured from a chip;
Fig. 23 is a diagram (No. 2) showing the V_{xy}-I_N characteristic measured from the chip;
Fig. 24 is a diagram (No. 3) showing the V_{xy}-I_N characteristic measured from the chip;
Fig. 25 is a diagram (No. 4) showing the V_{xy}-I_N characteristic measured from the chip;
Fig. 26 is a diagram (No. 5) showing the V_{xy}-I_N characteristic measured from the chip;
Fig. 27 is a diagram (No. 6) showing the V_{xy}-I_N characteristic measured from the chip; and
Fig. 28 is a diagram (No. 7) showing the V_{xy}-I_N characteristic measured from the chip.

Best Mode for Carrying Out the Invention

[0008] Hereinbelow, an embodiment of the present invention will be described with reference to the drawings.

[0009] First, an N-shaped nonlinear resistor circuit will be described. Here, a suffix Λ is indicated as reference symbol $_{\underline{A}}$ for the convenience of indication.

[0010] Fig. 1 is a diagram showing an N-shaped nonlinear resistor circuit using floating gate MOSFETs according to the present invention. Fig. 2 are diagrams (numerical simulations) showing various V_{xy}-$I_{\underline{A}}$ characteristics in Fig. 1, Fig. 2(a) is a diagram showing the characteristic with a voltage. $V_{\underline{xA}}$ as a parameter, Fig. 2(b) is a diagram showing the characteristic with a voltage $V_{\underline{yA}}$ as a parameter, Fig. 2(c) is a diagram showing the characteristic with a voltage $V_{\underline{nA}}$ as a parameter, and Fig. 2(d) is a diagram showing the characteristic with a voltage $V_{\underline{pA}}$, as a parameter. Fig. 3 are diagrams (numerical simulations) showing various V_{xy}-I_V characteristics in Fig. 1, Fig. 3(a) is a diagram showing the characteristic with a voltage V_{xV} as a parameter, Fig. 3(b) is a diagram showing the characteristic with a voltage V_{yV} as a parameter, Fig. 3(c) is a diagram showing the characteristic with a voltage V_{nV} as a parameter, and Fig. 3(d) is a diagram showing the characteristic with a voltage V_{pV} as a parameter.

[0011] Referring to Fig. 1, the circuit is formed by connecting in parallel a Λ-shaped nonlinear resistor circuit 1 and a V-shaped nonlinear resistor circuit 2 using multi-input floating gate MOSFETs (refer to reference document (1)). Figs. 2 and 3 show the nonlinear resistor characteristics of the currents $I_{\underline{A}}$ and I_V, respectively, in Fig. 1 for the voltage V_{xy}.

[0012] First, the Λ-shaped nonlinear resistor circuit 1 will be described.

[0013] Referring to Fig. 1, at a multi-input floating gate P-channel MOSFET $M_{\underline{pA}}$, capacitors $C_{\underline{p2A}}$ and $C_{\underline{p1A}}$ are connected to a gate terminal of a normal P-channel MOSFET and they are set as input terminals. Inputs are applied via the capacitors $C_{\underline{p2A}}$ and $C_{\underline{p1A}}$, thereby equivalently setting the gate terminal of the P-channel MOSFET $M_{\underline{pA}}$ floating. An N-channel MOSFET $M_{\underline{nA}}$ is serially connected to the P-channel MOSFET $M_{\underline{pA}}$.

[0014] Next, the V-shaped nonlinear resistor circuit 2 will be described.

[0015] Referring to Fig. 1, at the multi-input floating gate N-channel MOSFET M_{nV}, capacitors C_{n1V} and C_{n2V} are connected to a gate terminal of a normal N-channel MOSFET and they are set as input terminals. Inputs are applied via the capacitors C_{n1V} and C_{n2V}, thereby equivalently setting the gate terminal of the N-channel MOSFET M_{nV} floating. A P-channel MOSFET M_{pV} is serially connected to the N-channel MOSFET M_{nV}.

[0016] Referring to Figs. 1 and 2, it is understood that various V_{xy}-$I_{\underline{A}}$ and V_{xy}-I_V characteristics are obtained depending on the voltages shown in Fig. 1 (refer to the reference document (1)). In the circuit shown in Fig. 1, currents $I_{\underline{A}}$ and I_V are added, thereby combining various N-shaped V_{xy}-I_N characteristics.

[0017] A theoretical formula for describing the characteristics for control voltages of $I_{\underline{A}}$ and I_V is shown in the reference document (1). Here, the characteristics are simply expressed as follows.

$$I_{\underline{A}} = f_{\underline{A}}\,(V_{xy}, V_{\underline{xA}}, V_{\underline{yA}}, V_{\underline{nA}}, V_{\underline{pA}}), \tag{1}$$

$$I_V = f_V(V_{xy}, V_{xV}, V_{yV}, V_{nV,}\ V_{pV),} \tag{2}$$

Then, referring to Fig. 1,

$$I_N = I_{\underline{A}} + I_V$$
$$= f_{\underline{A}}(V_{xy}, V_{\underline{xA}}, V_{\underline{yA}}, V_{\underline{nA}}, V_{\underline{pA}}) + f_V(V_{xy}, V_{xV}, V_{yV}, V_{nV}, V_{pV}) \quad (3)$$

[0018] Fig. 4 are diagrams showing V-I characteristics approximate to a piecewise linearity according to the present invention. Fig. 4(a) shows the characteristic of the third order, Fig. 4(b) shows the characteristic of the fourth order, Fig. 4(c) shows the characteristic of the fifth order, Fig. 4(d) shows the characteristic of the sixth order, and Fig. 4(e) shows the characteristic of the seventh order.

[0019] The V_{xy}-I_N characteristics obtained in Fig. 1 continuously change. In the following, these characteristics are approximate to the characteristics of the piecewise linear functions of the third to seventh orders as shown in Fig. 4 and they are described. Here, the number of piecewise linear sections is called an order. Further, the end point in the piecewise linear section is called a break point.

[0020] A simple and qualitative description is given of a method for realizing each characteristic shown in Fig. 4

[0021] First, the characteristic of the third order shown in Fig. 4(a) is obtained by moving in parallel in the left and right directions the V_{xy}-$I_{\underline{A}}$ and V_{xy}-I_V characteristics shown in Figs. 2 and 3 by the voltage $V_{\underline{xA}}$ or $V_{\underline{yA}}$ and the voltage V_{xV} or V_{yV} shown in Fig. 1. In this case, the center portion of the V_{xy}-I_N characteristic may entirely be one linear piecewise. In order to realize this, preferably, the negative portions of the Λ-shaped and V-shaped characteristics may be linear as much as possible. That is, the setting of $V_{\underline{nA}}$, $V_{\underline{pA}}$, V_{nV}, and V_{pV} is important. This state is shown in Fig. 5.

[0022] Similarly to the above description, the fourth to seventh characteristics are realized. These characteristics are different from the characteristics of the third order and the break point is necessary for the center portion of the characteristics. This is realized by adjusting the voltage $V_{\underline{pA}}$ and V_{nV} in Fig. 1. The fourth order characteristic is realized by adjusting the inclination of the negative portion of the V_{xy}-$I_{\underline{A}}$ or V_{xy}-I_V characteristic. The fifth order characteristic is realized by simultaneously adjusting both the Λ-shaped and V-shaped characteristics. The sixth order characteristic is realized by moving in parallel in the lateral axis direction the Λ-shaped and V-shaped characteristics used for the fourth order characteristic by the voltage $V_{\underline{xA}}$, or $V_{\underline{yA}}$ and the voltage V_{xV} or V_{yV} in Fig. 1. The seventh order characteristic is obtained by the same method based on the fifth order characteristic.

[0023] In the characteristics of the third to seventh orders, the inclination of the piecewise linear function and the break points may be changed. This will be described in detail with the characteristics of the third and fifth orders that are usually used.

(1) Characteristic of the third order

[0024] By the following method, current-axis coordinates I_{BP-} and I_{BP+} of the break points in Fig. 4(a) are fixed and voltage-axis coordinates V_{BP-} and V_{BP+} are changed. Thus, only an inclination m_0 is changed. First, the voltages V_{BP-} and V_{BP+} are determined by the voltage $V_{\underline{xA}}$ or $V_{\underline{yA}}$ and the voltage V_{xV} or V_{yv}. Next, the currents I_{BP-} and I_{BP+} are adjusted by the voltages $V_{\underline{nA}}$, $V_{\underline{pA}}$, V_{nV}, and V_{pv} without changing the voltages V_{BP-} and V_{BP+}, and the inclination m_0 is determined. In this case, since the currents I_{BP-} and I_{BP+} need to be fixed, particularly, the voltages $V_{\underline{pA}}$ and V_{nV} are important parameters.

[0025] Next, a method for adjusting break points B_{P-} and B_{P+} while fixing the inclination m_0 is shown. First, the voltages V_{BP-} and V_{BP+} are determined by the voltages $V_{\underline{xA}}$ or $V_{\underline{yA}}$ and the voltage V_{xV} or V_{yv}. Next, the break points B_{P-} and B_{P+} are enlarged or reduced in the voltage axis direction mainly by the voltages $V_{\underline{nA}}$ and V_{pV}, thus to shift the break points.

(2) Fifth order characteristic

[0026] For the fifth order characteristic, four break points B_{P1-}, B_{P1+}, B_{P2-}, and B_{P2+} are fixed in Fig. 4(c), and the inclinations m_0 and m_1 can be adjusted. In the change of only the inclination m_0, the change of inclination of the negative resistor portions of the Λ-shaped and V-shaped characteristics are used. Therefore, the voltages $V_{\underline{pA}}$ and V_{nV} are important parameters. The inclination m_1 can be adjusted by the voltages $V_{\underline{yA}}$ and V_{yv}. After that, other voltages adjust the break points.

[0027] The break points are changed while fixing the inclinations m_0 and m_1 as follows. The break point B_{P1-} or B_{P1+} is changed by enlarging the characteristics of the voltages $V_{\underline{nA}}$ and V_{pV} in the longitudinal axis direction and changing the length of the piecewise linear portion of the inclination m_1. Similarly to the change of the break points of the char-

acteristic of the third order, the break point B_{P2-} or B_{P2+} is adjusted by enlarging or reducing the break point H_{P2-} or B_{P2+} in the voltage-axis direction and in the current-axis direction by the voltage $V_{\underline{pA}}$, $V_{\underline{xA}}$, or $V_{\underline{yA}}$ and the voltage V_{nV}, $V_{xV,}$ or $V_{yV.}$ In this case, the fine adjustment with other control voltages is necessary.

[Neumerical simulations]

[0028] Hereinbelow, the N-shaped nonlinear resistor characteristics of the third to seventh orders are confirmed by computer simulations using the V-I characteristic formula using the simple MOSFET-model derived from reference document (1). Particularly, with the characteristics of the third to fifth orders, the adjusting states of the break points and inclinations are indicated in detail. In the simulation experiments, transconductance parameters of the N-channel MOSFET and P-channel MOSFET in Fig. 1 are $K_n = K_p = 300\ \mu A/V^2$, a threshold voltage of the N-channel MOSFET is $V_{tn} = 0.55$ V, and a threshold voltage of the P-channel MOSFET is $V_{tp} = -0.8$ V. Further, referring to Fig. 1, $C_{\underline{p1A}} = C_{\underline{p2A}} = C_{n1v} = C_{n2v} = 0.1$ pF.

(1) Nonlinear resistor characteristic of the third order

[0029] Referring to Fig. 6, the characteristic approximates to the third order piecewise linearity is shown in the case of using the voltage values in Table 1. A characteristic A has the same inclination m_0 with a characteristic C in Fig. 6 and the break point of the characteristic A is different from the characteristic C. On the contrary, a characteristic B has the same currents I_{P1-} and T_{P1+} as those of the characteristic C and the inclination m_0 of the characteristic B is different from that of the characteristic C. As a result, the break points B_{P-} and B_{P+} and the inclination m_0 shown in Fig. 4 are changed.

Table 1

	Characteristics in Fig. 6		
Voltages in Fig. 1	A	B	C
$V_{\underline{xA}}$ [V]	-5.9	-5.9	-4.4
$V_{\underline{yA}}$ [V]	0	0	0
$V_{\underline{nA}}$ [V]	3.7	2.5	2.95
$V_{\underline{pA}}$ [V]	-4.1	-5.3	-4.1
V_{xv} [V]	5.9	5.9	4.4
V_{yv} [V]	0	0	0
V_{nv} [V]	3.7	5.9	3.7
V_{pv} [V]	-3.9	-2.7	-3.15

[0030] See Table 1 and Fig. 6, the break points are determined depending on the voltages $V_{\underline{nA}}$ and V_{pV}, and the inclination m_0 is greatly changed by the voltages $V_{\underline{pA}}$ and V_{nV}.

(2) Fifth order nonlinear resistor characteristic

[0031] Examples of the V_{xy}-I_N characteristic approximates to the fifth order piecewise linear characteristic obtained by the simulation are shown in Figs. 7, 8, and 9. Further, values of control voltages for the characteristics in Figs. 7, 8, and 9 are shown in Tables 2 to 4.

Table 2

	Characteristics in Fig. 7		
Voltages in Fig. 1	A	B	C
V_{xA} [V]	-3.95	-3.95	-4.05
V_{yA} [V]	0	0.1	0.38
V_{nA} [V]	1.55	1.55	1.65
V_{pA} [V]	-5.15	-5.4	-4.2
V_{xV} [V]	3.95	3.95	4.05
V_{yV} [V]	0	-0.1	-0.38
V_{nV} [V]	4.65	4.9	3.7
V_{pV} [V]	-1.8	-1.8	-1.9

Table 3

	Characteristics in Fig. 8		
Voltages in Fig. 1	A	B	C
V_{xA} [V]	-3.7	-3.9	-4.1
V_{yA} [V]	0	0.1	0.13
V_{nA} [V]	1.35	1.525	1.7
V_{pA} [V]	-5	-5.7	-6.1
V_{xV} [V]	3.7	3.9	4.1
V_{yV} [V]	0	-0.1	-0.13
V_{nV} [V]	4.7	5.2	5.6
V_{pV} [V]	-1.6	-1.775	-1.95

Table 4

	Characteristics in Fig. 9		
Voltages in Fig. 1	A	B	C
V_{xA} [V]	-3.4	-3.95	-5
V_{yA} [V]	0.135	0.1	0.1
V_{nA} [V]	1.535	1.55	1.55
V_{pA} [V]	-4.93	-5	-6.1
V_{xV} [V]	3.4	3.95	5
V_{yV} [V]	-0.135	-0.1	-0.1
V_{nV} [V]	4.43	4.5	5.5
V_{pV} [V]	-1.765	-1.8	-1.8

[0032] Curves B and C in Fig. 7 are shown as examples by changing the inclination m_0 with the fixing of the voltage coordinates of the four break points in Fig. 4(c). Similarly, curves A and B are shown by changing the inclination m_1 as examples. Based on the examples and Table 2, the voltages V_{pA} and V_{nV} may be changed while keeping the voltages V_{nA} and V_{pV} constant in the case of adjusting the inclination m_0. Further, the inclination m_1 may be adjusted by coarsely determining the characteristic with the voltages V_{yA} and V_{yV}, and by using the voltages V_{pA} and V_{nV} for fine tuning.

[0033] Fig. 8 and Table 3 show an example of adjusting the break points B_{P1-} and B_{P1+} while fixing the inclinations m_0 and m_1 in Fig. 4(c). Fig. 9 and Table 4 show an example of adjusting the break points B_{P2-} and B_{P2+}. Based on the simulation experiments, the break points B_{P1+} and B_{P1-} are determined depending on the voltages V_{pV} and V_{nA}, respectively. Further, the break points B_{P2+} and B_{P2-} are determined depending on the voltages V_{xV} and V_{nV} and the voltages V_{xA} and V_{pA}, respectively.

(3) Fourth, sixth, and seventh order nonlinear resistor characteristics

[0034] Fig. 10 shows the fourth order nonlinear resistor characteristic, Fig. 11 shows the sixth order nonlinear resistor characteristic, and Fig. 12 shows the seventh order nonlinear resistor characteristic. The voltages in Fig. 1 used for the characteristics are shown in Tables 5 to 7.

Table 5

	Characteristics in Fig. 10	
Voltages in Fig. 1	A	B
V_{xA} [V]	-4.4	-4.4
V_{yA} [V]	0	0
V_{nA} [V]	2.6	1.55
V_{pA} [V]	-4	-6
V_{xV} [V]	4.4	4.4
V_{yV} [V]	0	0
V_{nV} [V]	5.5	3.7
V_{pV} [V]	-1.8	-2.75

Table 6

	Characteristics in Fig. 11	
Voltages in Fig. 1	A	B
V_{xA} [V]	-6	-6
V_{yA} [V]	0	0
V_{nA} [V]	2.6	1.55
V_{pA} [V]	-4	-6
V_{xV} [V]	6	6
V_{yV} [V]	0	0
V_{nV} [V]	5.5	3.7
V_{pV} [V]	-1.8	-2.75

Table 7

Voltages in Fig. 1	
V_{xA} [V]	-5.5
V_{yA} [V]	0.1
V_{nA} [V]	1.55

Table 7 (continued)

Voltages in Fig. 1	
V_{pA} [V]	-5.4
V_{xV} [V]	5.5
V_{yV} [V]	-0.1
V_{nV} [V]	4.9
V_{pV} [V]	-1.8

[0035] With Table 5 and C in Table 1, the fourth order characteristic is obtained by changing the voltages V_{nA}, V_{pA}, V_{nV}, and V_{pV} based on the characteristic of the third order. Further, with Tables 5 and 6, Table 7, and B in Table 2, the sixth and seventh order characteristics are obtained by changing the voltages V_{xA} and V_{xV} based on the fourth and fifth order characteristics, respectively.

[HSPICE simulations]

[0036] Semiconductor process parameters of MOSIS TSMC 0.35 μm CMOS process is used, and the sizes of M_{nA} and M_{nV} in Fig. 1 have W of 20 μm and L of 0.4 μm. Further, the sizes of M_{pA} and M_{pV} in Fig. 1 have W of 60 μm and L of 0.4 μm. Figs. 13 and 14 show results of circuit simulations using HSPICE in the case of capacitances $C_{p1A} = C_{p2A} = C_{n1V} = C_{n2V} = 0.1$ pF. The characteristics correspond to the simulation characteristics of the third to seventh orders, respectively.

[0037] As mentioned above, the N-shaped nonlinear resistor circuit is provided with the multi-input floating gate MOSFETs. Further, the numeral calculations and the HSPICE simulations are used to show examples of the V-I characteristics. Further, a method for realizing the characteristics is qualitatively described.

[Experiments using discrete parts]

[0038] According to the embodiment, the circuit in Fig. 15 comprises discrete parts, and the V_{xy}-I_N characteristic is measured. The circuit is shown in Fig. 15. $M_{nA}11$ and $M_{nV}12$ use 2SK612 and $M_{pA}13$ and $M_{pV}14$ use 2SJ133. Further, experimental results are shown in Figs. 16 to 20 when capacitances $C_{p1A}15$, $C_{p2A}16$, $C_{n1V}17$, and $C_{n2V}18$ are 0.1 μF. The voltage values in Fig. 15 for realizing the characteristics are shown in Tables 8 to 12.

[0039] Fig. 16 shows the experimental results using the discrete parts of the V_{xy}-I_N characteristic of the third order, and voltage values in Fig. 15 are V_A of -0.7V, V_{nA} of 1.55V, V_{pA} of -4.69V, V_V of 0.7V, V_{nV} of 3.23V, and V_{pV} of -2.32V as shown in Table 8.

Table 8

Voltages in Fig. 15	
V_A [V]	-0.7
V_{nA} [V]	1.55
V_{pA} [V]	-4.69
V_V [V]	0.7
V_{nV} [V]	3.23
V_{pV} [V]	-2.32

[0040] Fig. 17 shows the experimental results using the discrete parts of the fourth order V_{xy}-I_N characteristic, and voltage values in Fig. 15 are V_A of -1.6V, V_{nA} of 1.46V, V_{pA}, of -5.65V, V_V of 1V, V_{nV} of 3.43V, and V_{pV} of -2.28V as shown in Table 9.

Table 9

Voltages in Fig. 15	
V_A [V]	-1.6

Table 9 (continued)

Voltages in Fig. 15	
V_{nA} [V]	1.46
V_{pA} [V]	-5.65
V_V [V]	1
V_{nV} [V]	3.43
V_{pV} [V]	-2.28

[0041] Fig. 18 shows the experimental results using the discrete parts of the fifth order V_{xy}-I_N characteristic, and voltage values in Fig. 15 are V_A of -1.5V; V_{nA} of 1.46V, V_{pA} of -5.65V, V_V of 1.5V, V_{nV} of 4.23V, and V_{pV} of -2.18V as shown in Table 10.

Table 10

Voltages in Fig. 15	
V_A [V]	-1.5
V_{nA} [V]	1.46
V_{pA} [V]	-5.65
V_V [V]	1.5
V_{nV} [V]	4.23
V_{pV} [V]	-2.18

[0042] Fig. 19 shows the experimental results using the discrete parts of the sixth order V_{xy}-I_N characteristic, and voltage values in Fig. 15 are V_A of -2.1V, V_{nA} of 1.46V, V_{pA} of -5. 65V, V_V of 1. 6V, V_{nV} of 3.43V, and V_{pV} of -2.28V as shown in Table 11.

Table 11

Voltages in Fig. 15	
V_A [V]	-2.1
V_{nA} [V]	1.46
V_{pA} [V]	-5.65
V_V [V]	1.6
V_{nV} [V]	3.43
V_{pV} [V]	-2.28

[0043] Fig. 20 shows the experimental results using the discrete parts of the seventh order V_{xy}-I_N characteristic, and voltage values in Fig. 15 are V_A of -2.1V, V_{nA} of 1.46V, V_{pA} of -5.65V, V_V of 2.1V, V_{nV} of 4.23V, and V_{pV} of -2.18V as shown in Table 12.

Table 12

Voltages in Fig. 15	
V_A [V]	-2.1
V_{nA} [V]	1.46
V_{pA} [V]	-5.65
V_V [V]	2.1
V_{nV} [V]	4.23

Table 12 (continued)

Voltages in Fig. 15	
V_{pV} [V]	-2.18

[0044] A resistor R(19) is inserted between nodes A and B (on the power supply side of the above-mentioned non-linear resistor circuit) in Fig. 15, the voltage drop is amplified by an instrumentation amplifier (INA114) 20, and the current IN is obtained based on the amplified output voltages by the following formulae (4) to (6). Here, reference symbol R_G denotes resistance for determining gain G of the instrumentation amplifier 20, and R_G is 10 kΩ. Further, the resistance R is 33 Ω and output resistance R_o is 10 kΩ.

$$Vo = G \cdot (V_{IN}^{+} - V_{IN}^{-}) \quad (4)$$

$$G = I + (50\ k\Omega/R_G) \quad (5)$$

$$I_N = V_o/G \cdot R \quad (6)$$

[0045] Next, an example of an integrated circuit will be described.

[0046] The circuit shown in Fig. 15 is an integrated circuit fabricated through MOSIS TSMC 0.35 μm CMOS semiconductor process. The V_{xy}-I_N characteristic measuring circuit comprising the resistor 19 and the measuring amplifier shown in Fig. 15 is not integrated and is mounted outside of the chip by discrete parts. Fig. 21 shows a micro-photograph of the IC chip including the circuit shown in Fig. 15.

[0047] The sizes of M_{nA} and M_{nV} in Fig. 15 have W of 18 μm and L of 0.6 μm. Further, the sizes of M_{pA} and M_{pV} in Fig. 15 have W of 54 μm and L of 0.6 μm. Furthermore, the capacitances are $C_{p1A} = C_{p2A} = C_{n1V} = C_{n2V} = 0.3$ pF.

[0048] Figs. 22 to 28 show the V_{xy}-I_N characteristics which are measured from the chip. The voltage values in Fig. 15 for realizing the characteristics are shown in Tables 13 to 19. The characteristics correspond to the simulation characteristics of the third to seventh orders and the HSPICE simulation characteristics. Here, the current IN is obtained by the calculating formulae (4), (5), and (6), similarly to the experiment using discrete parts. The resistances in the calculating formulae (4), (5), and (6) are R_G of 240 kΩ, R of 10 Ω, and output resistance R_o of 10 kΩ.

Table 13

	Characteristics in Fig. 22		
Voltages in Fig. 15	A	B	C
V_A [V]	-1.65	-1.65	-1.45
V_{nA} [V]	1.18	1.11	1.42
V_{pA} [V]	-8.75	-8.97	-8.27
V_V [V]	1.65	1.65	1.45
V_{nV} [V]	7.76	7.96	7.06
V_{pV} [V]	-1.35	-1.35	-1.62

Table 14

	Characteristics in Fig. 23	
Voltages in Fig. 15	A	B
V_A [V]	-1.65	-1.65
V_{nA} [V]	0.77	0.64
V_{pA} [V]	-8.17	-9.8
V_V [V]	1.65	1.65
V_{nV} [V]	8.82	7.25
V_{pV} [V]	-0.81	-0.9

Table 15

	Characteristics in Fig. 24		
Voltages in Fig. 15	A	B	C
V_A [V]	-1.59	-1.65	-1.65
V_{nA} [V]	0.87	0.86	0.89
V_{pA} [V]	-9.4	-9.4	-9
V_V [V]	1.59	1.65	1.65
V_{nV} [V]	8.26	8.26	7.86
V_{pV} [V]	-1.02	-1.02	-1.06

Table 16

	Characteristics in Fig. 25		
Voltages in Fig. 15	A	B	C
V_A [V]	-1.65	-1.65	-1.65
V_{nA} [V]	0.86	0.92	0.96
V_{pA} [V]	-9.4	-9.4	-9
V_V [V]	1.65	1.65	1.65
V_{nV} [V]	8.26	8.26	7.86
V_{pV} [V]	-1.02	-1.09	-1.14

Table 17

	Characteristics in Fig. 26		
Voltages in Fig. 15	A	B	C
V_A [V]	-1.45	-1.55	-1.65
V_{nA} [V]	1.12	0.97	0.86
V_{pA} [V]	-8.81	-9.54	-9.4
V_V [V]	1.45	1.55	1.65
V_{nV} [V]	7.6	8.28	8.26
V_{pV} [V]	-1.29	-1.15	-1.02

Table 18

Voltages in Fig. 15	Characteristics in Fig. 27 A	Characteristics in Fig. 27 B
$V_{\underline{A}}$ [V]	-1.65	-1.65
$V_{\underline{nA}}$ [V]	0.77	0.64
$V_{\underline{pA}}$ [V]	-8.17	-8.86
V_v [V]	1.65	1.65
V_{nv} [V]	7.79	7.25
V_{pv} [V]	-0.81	-0.9

Table 19

Voltages in Fig. 15	
$V_{\underline{A}}$ [V]	-1.65
$V_{\underline{nA}}$ [V]	0.65
$V_{\underline{pA}}$ [V]	-8.86
V_V [V]	1.65
V_{nV} [V]	7.79
V_{pV} [V]	-0.81

[0049] Another embodiment may be realized by moving in parallel the Λ-shaped and V-shaped characteristics in lateral axis direction by the following in Fig. 1.

(1) $V_{\underline{xA}}$ and V_{yV}
(2) $V_{\underline{yA}}$ and V_{xV}
(3) $V_{\underline{xA}}$, $V_{\underline{yA}}$, V_{xV}, and V_{yV}

[0050] According to the present invention, the control voltages in the circuit are adjusted, thereby obtaining various V-I characteristics that can be approximated to the piecewise linear functions of the third to seventh orders. Further, the various V-I characteristics are integrated as an IC form and are applied to an oscillating circuit and chaos generating circuit.

[0051] Specifically, since the N-shaped nonlinear resistor characteristic of the N-shaped nonlinear resistor circuit according to the present invention has a negative resistance area in the center, it is widely applied to the oscillating circuit and neuron circuit. In particular, the characteristic approximates to the characteristics of the third or fifth order can form a sine wave oscillating circuit and chaos generating circuit by the combination to L or C.

[0052] As mentioned above, the V-I characteristics approximate to the piecewise linear characteristics of the third to seventh orders are realized. Further, the V-I characteristic is easily variously changed by the external voltages. Although the fourth or sixth order characteristic is not widely used, it can easily be realized and therefore the additional application for the oscillating circuit is expected.

[0053] Further, the N-shaped nonlinear resistor circuit using the floating gate MOSFETs of the present invention can be integrated in the standard CMOS semiconductor process and enables the integrated circuit for various applications.

[0054] The circuit having the N-shaped voltage-current characteristic can widely be used for the sine wave oscillating circuit, double-scroll chaos circuit, and neuron circuit. This circuit structure is easily integrated as an IC form and

therefore can be applied to various integrated circuits necessary for sine waves and chaos oscillating circuits. Further, the fourth or sixth order nonlinear characteristic that is not conventionally used is realized and therefore can be applied to another circuit.

[0055] The present invention is not limited to the above embodiment, can variously be modified based on the essentials of the present invention, and various modifications are not excluded from the range of the present invention.

[0056] As mentioned above in detail, according to the present invention, the following advantages are obtained.

(1) Since various N-shaped V-I characteristics are realized by the characteristics approximate to the piecewise linear functions of the third to seventh orders and they can variously be changed by the external voltages.
(2) The integration is realized by the standard CMOS semiconductor process and various applying circuits are integrated as a circuit.

Industrial Applicabilities

[0057] A nonlinear resistor circuit using floating gate MOSFETs according to the present invention is suitable as a device indicating an N-shaped voltage-current characteristic that is important as the basic components such as an oscillating circuit, chaos generating circuit, or neuron circuit, and is expected to be applied to a voltage control sine wave oscillating circuit, voltage control chaos oscillating circuit, dynamic neuron circuit, and memory circuit.

Claims

1. A nonlinear resistor circuit using a floating gate MOSFETs, wherein a Λ-shaped nonlinear resistor circuit using a multi-input floating gate MOSFET and a V-shaped nonlinear resistor circuit using a multi-input floating gate MOSFET are connected in parallel therewith and current of said Λ-shaped nonlinear resistor circuit and current of said V-shaped nonlinear resistor circuit are added, thus to combine various N-shaped voltage-current characteristics.

2. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 1, wherein said N-shaped voltage current characteristic is continuously changed.

3. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 2, wherein the voltage-current characteristics approximate to piecewise linear characteristics of third to seventh orders are realized.

4. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein negative resistor portions in the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and in the voltage-current characteristic of said V-shaped nonlinear resistor circuit are linear as much as possible, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between an input terminal of said Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of said V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the characteristic of the third order.

5. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein negative resistor portions in the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are linear as much as possible, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of said Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of said V-shaped nonlinear resistor circuit, thus to combine the characteristic of the third order.

6. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein an inclination of a negative portion of the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of said V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of said V-shaped nonlinear resistor circuit is moved in parallel in the left and right directions by a voltage between an input terminal of said Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of said V-shaped nonlinear resistor circuit and a drain terminal

of a P-channel MOSFET, thus to combine the fourth order characteristic.

7. The nonlinear resistor circuit using the floating gate. MOSFETs according to Claim 3, wherein an inclination of a negative portion of the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of said V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of said V-shaped nonlinear resistor circuit is moved in parallel in the left and right directions by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of said Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of said V-shaped nonlinear resistor circuit, thus to combine the fourth order characteristic.

8. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein inclinations of negative portions of both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between an input terminal of said Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of said V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the fifth order characteristic.

9. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein inclinations of negative portions of both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the left and right directions by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of said Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of said V-shaped nonlinear resistor circuit, thus to combine the fifth order characteristic.

10. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein an inclination of a negative portion of the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of said V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between an input terminal of said Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of said V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the sixth order characteristic.

11. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein an inclination of a negative portion of the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit or the voltage-current characteristic of said V-shaped nonlinear resistor circuit is adjusted to change the inclination of the characteristic, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of said Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of said V-shaped nonlinear resistor circuit, thus to combine the sixth order characteristic.

12. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein inclinations of negative portions of both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between an input terminal of said Λ-shaped nonlinear resistor circuit and a drain terminal of an N-channel MOSFET and a voltage between an input terminal of said V-shaped nonlinear resistor circuit and a drain terminal of a P-channel MOSFET, thus to combine the seventh order characteristic.

13. The nonlinear resistor circuit using the floating gate MOSFETs according to Claim 3, wherein inclinations of negative portions of both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current

characteristic of said V-shaped nonlinear resistor circuit are adjusted to change the inclinations of the characteristics, and both the voltage-current characteristic of said Λ-shaped nonlinear resistor circuit and the voltage-current characteristic of said V-shaped nonlinear resistor circuit are moved in parallel in the lateral axis direction by a voltage between the ground and a drain terminal of a floating gate P-channel MOSFET of said Λ-shaped nonlinear resistor circuit and a voltage between the ground and a drain terminal of a floating gate N-channel MOSFET of said V-shaped nonlinear resistor circuit, thus to combine the seventh order characteristic.

F I G. 1

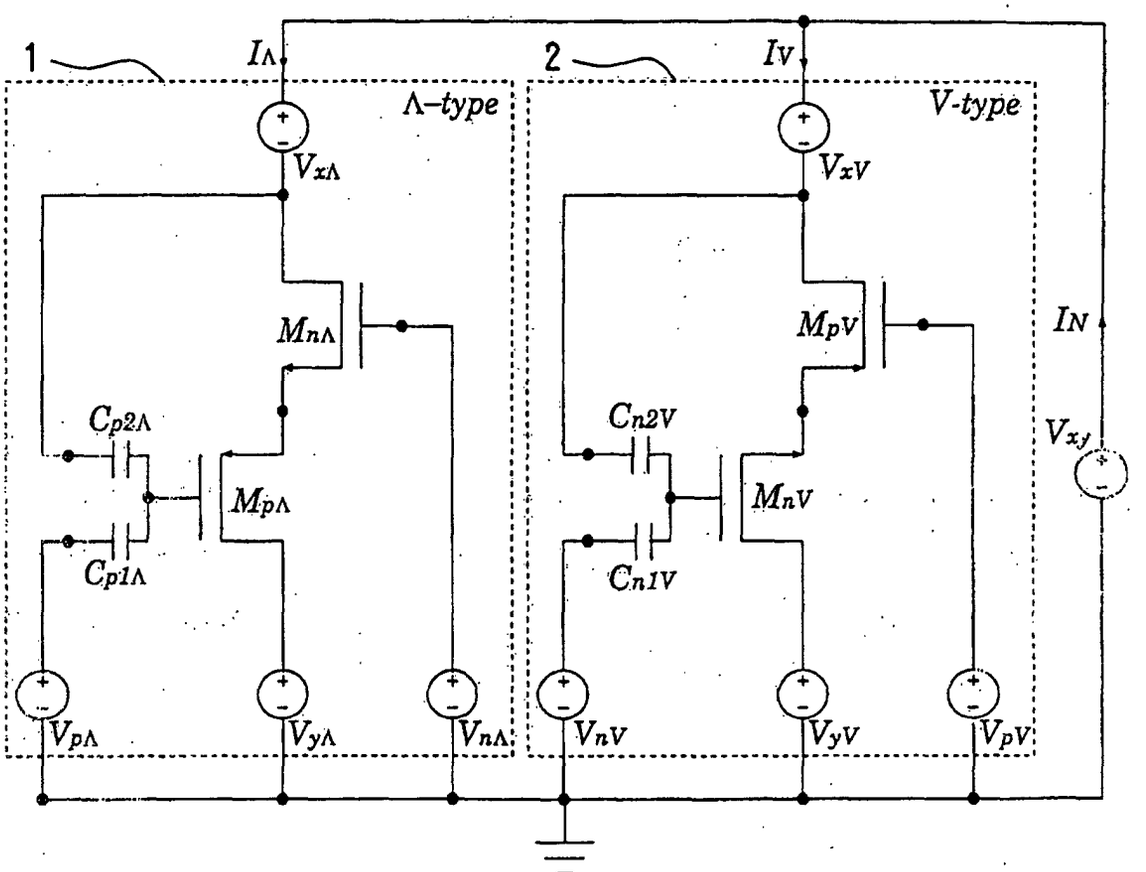
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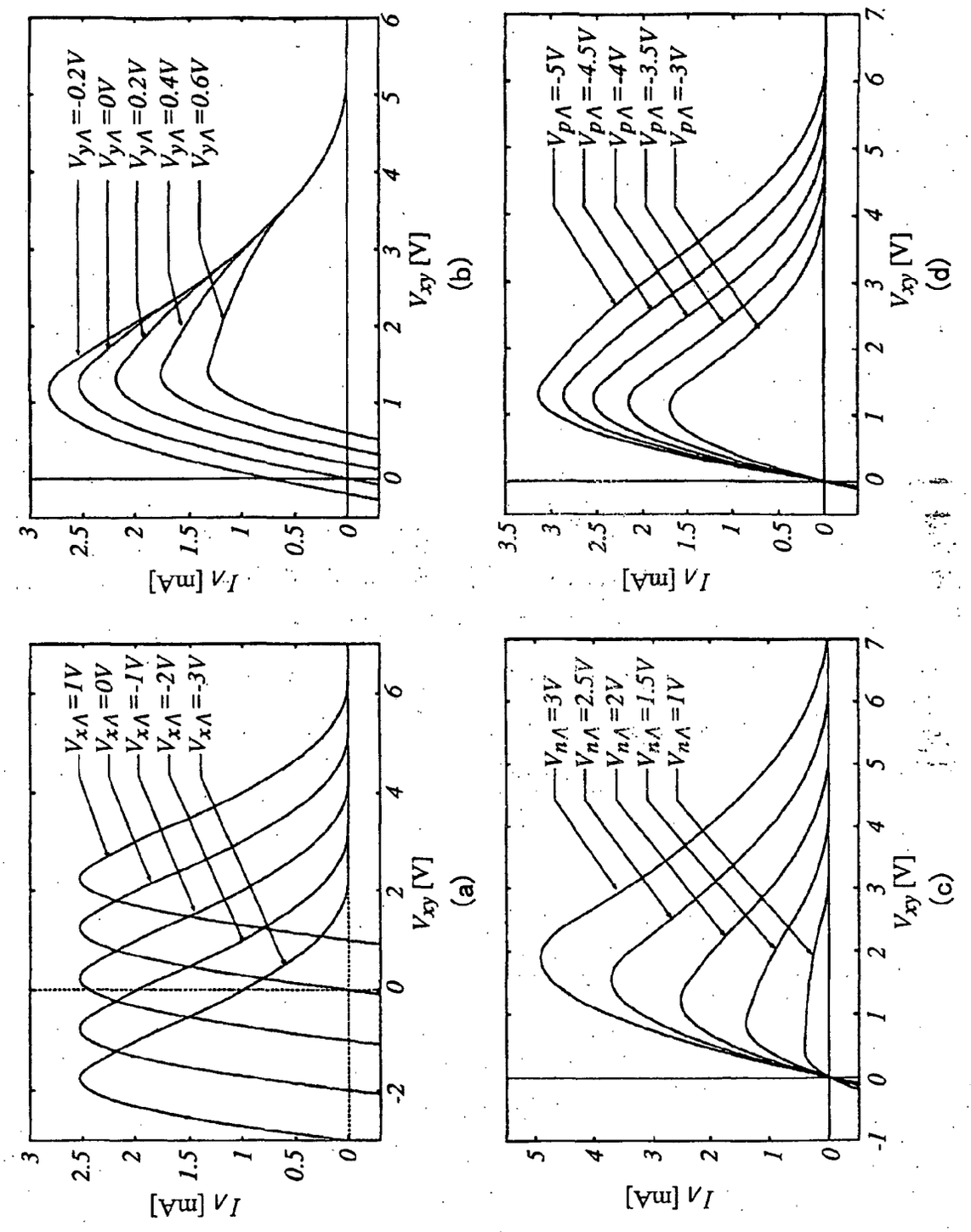
FIG. 2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I_A [mA]
V_{xy} [V]
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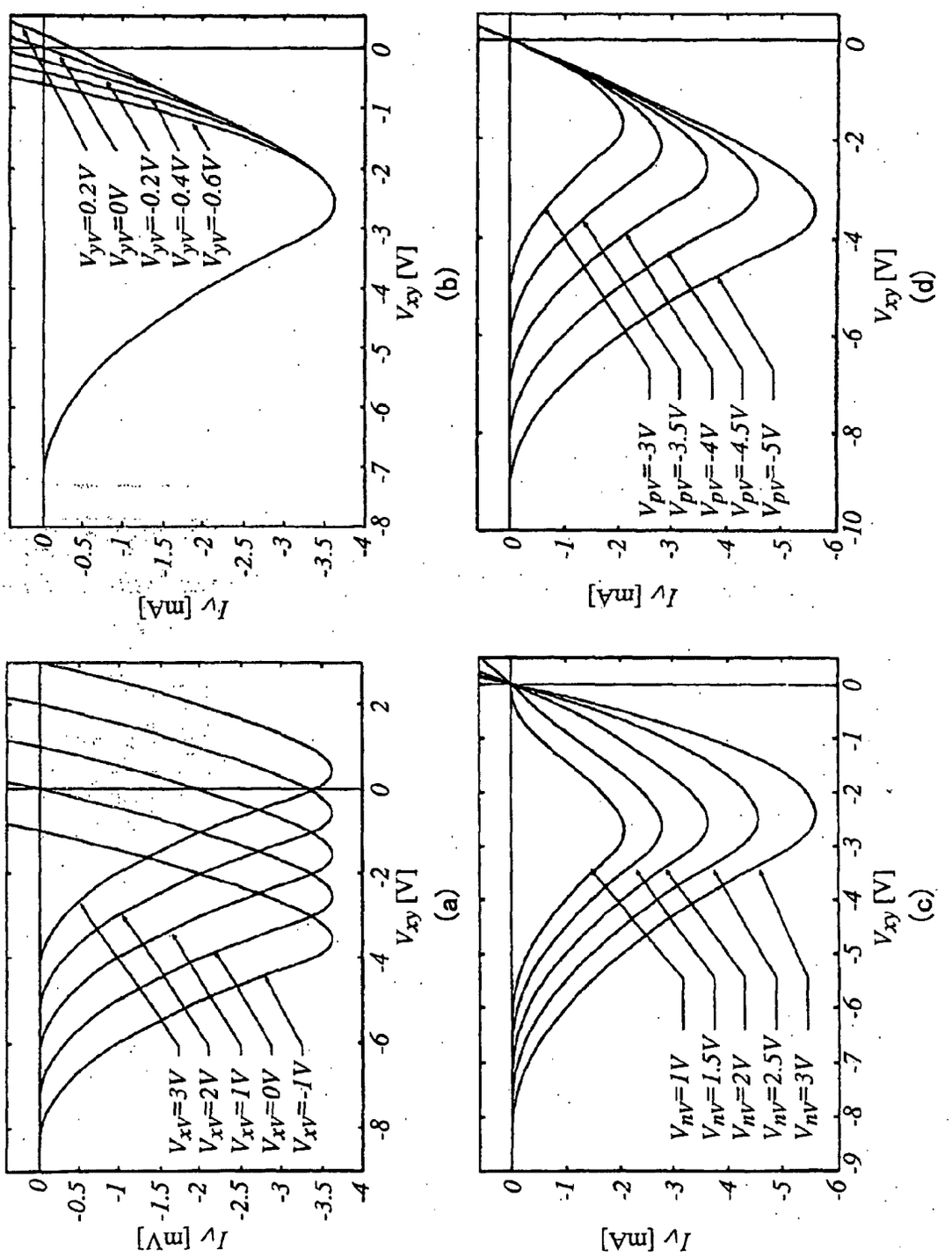
(d)

FIG. 3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V_{yv}=-0.6V
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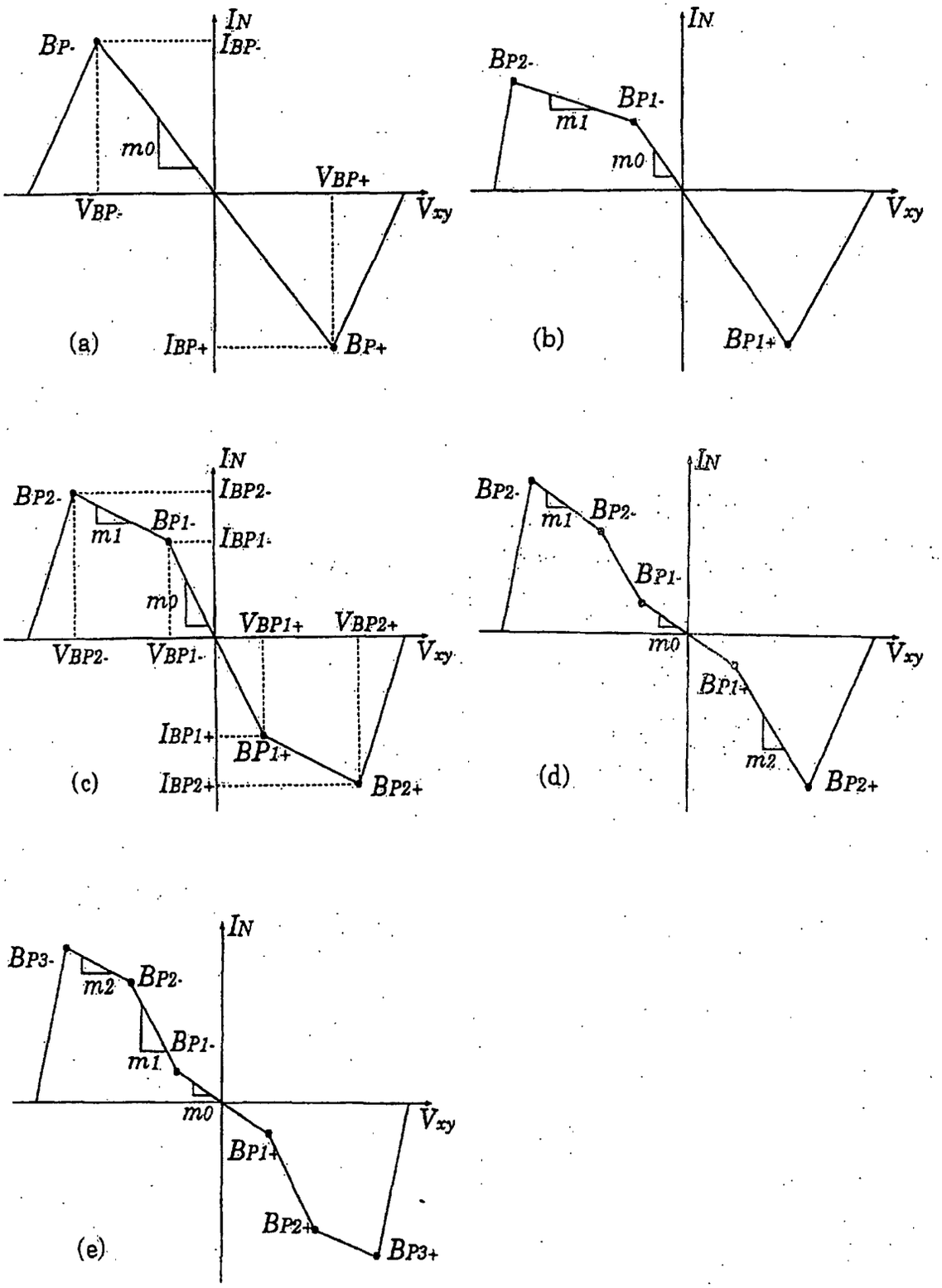
FIG. 4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VBP2-
VBP1-
IBP1+
BP1+
IBP2+
BP2+
(d)
m2
(e)
BP3-
BP3+

FIG. 5

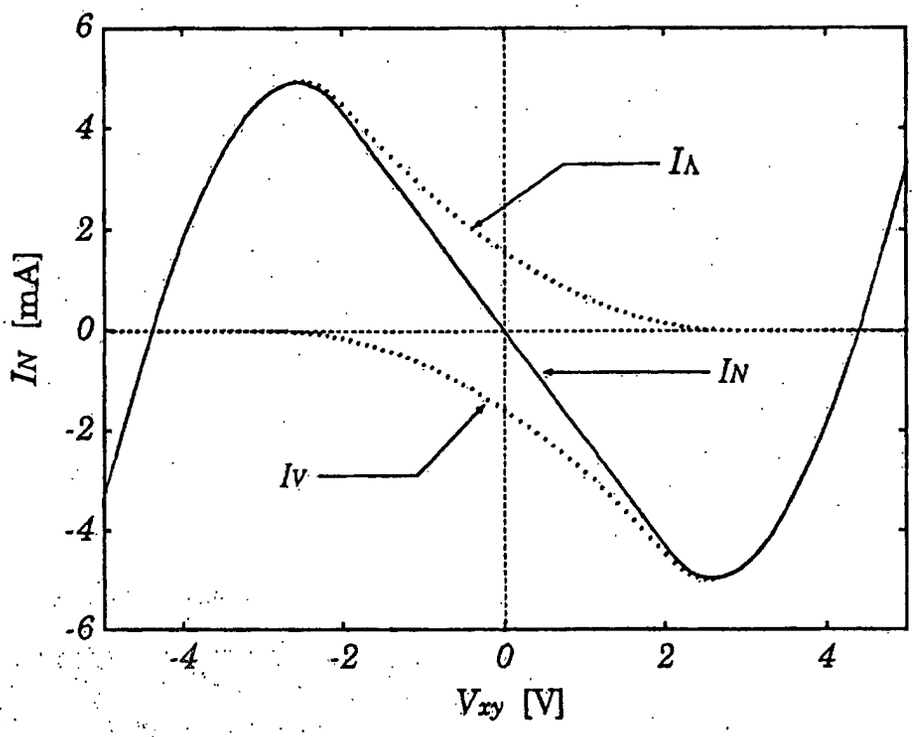

6
4
2
0
-2
-4
-6
-4
-2
0
2
4
I_N [mA]
V_{xy} [V]
I_A
I_N
I_V

FIG. 6

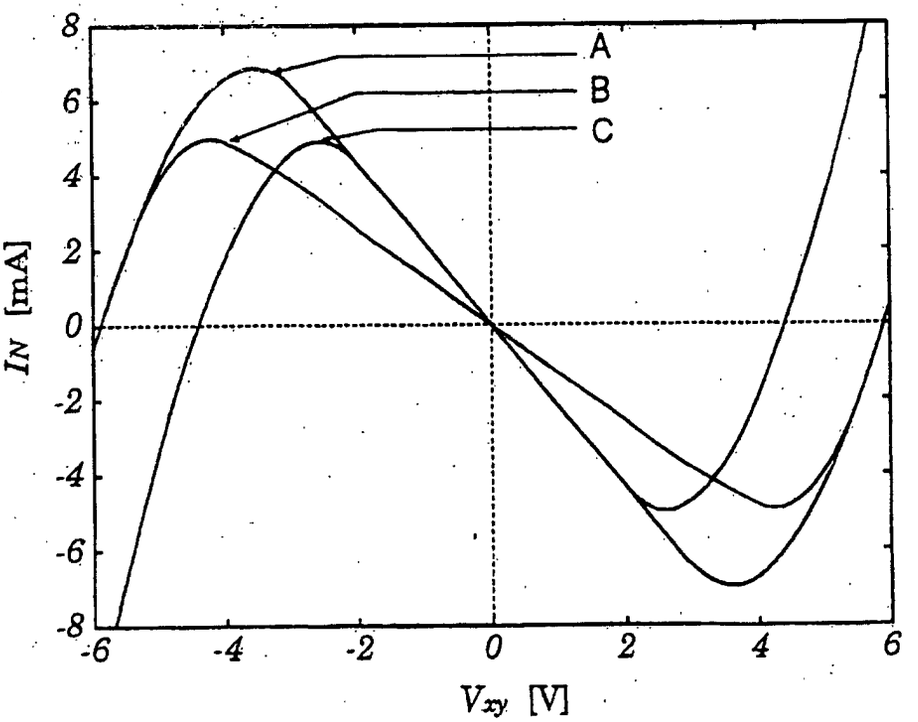

8
6
4
2
0
-2
-4
-6
-8
-6
-4
-2
0
2
4
6
I_N [mA]
V_{xy} [V]
A
B
C

FIG. 7

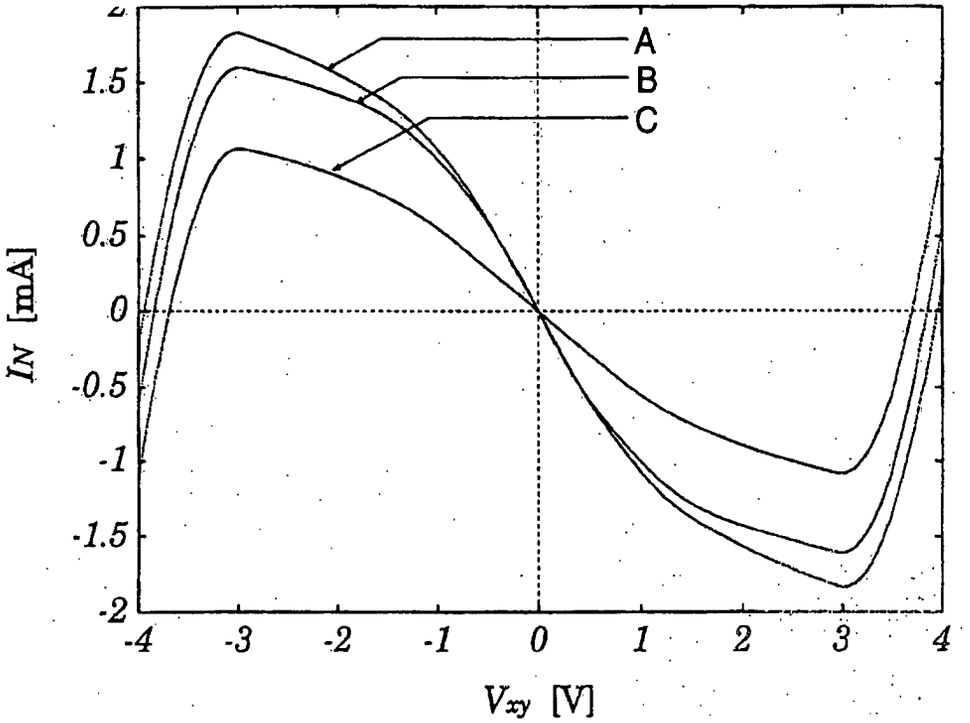

A
B
C
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-4
-3
-2
-1
0
1
2
3
4
I_N [mA]
V_{xy} [V]

FIG. 8

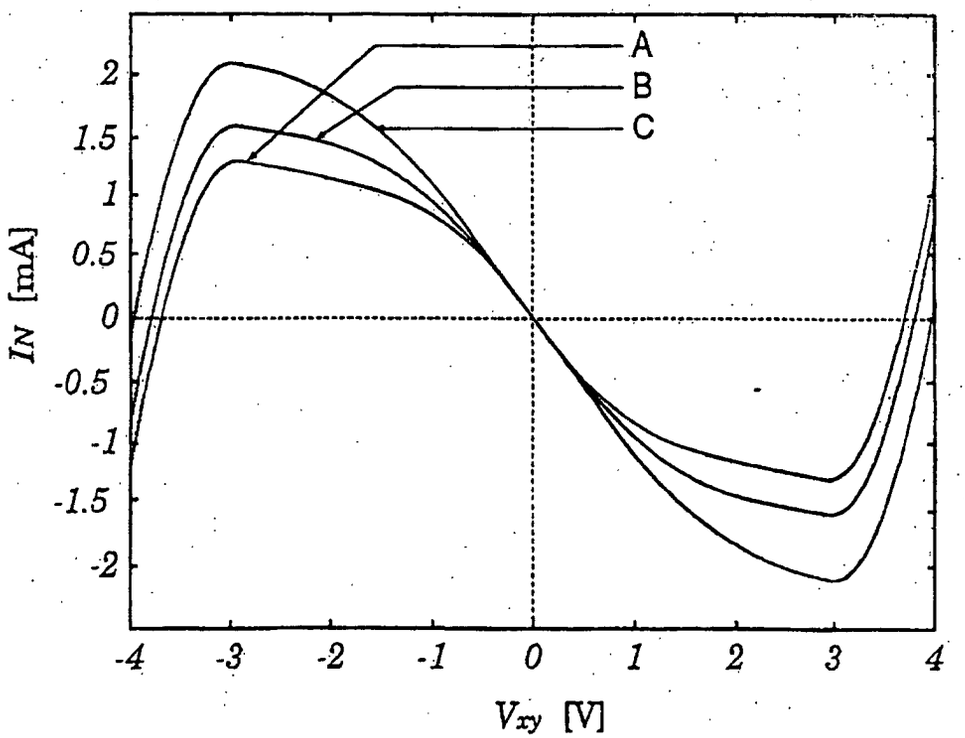

A
B
C
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-4
-3
-2
-1
0
1
2
3
4
I_N [mA]
V_{xy} [V]

FIG. 9

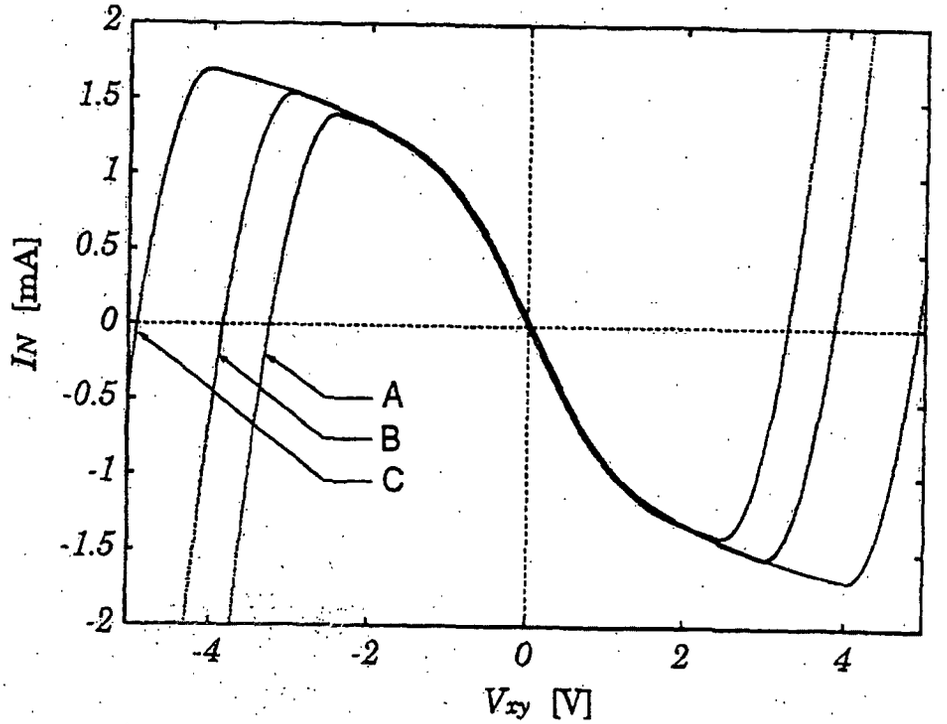

2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-4
-2
0
2
4
I_N [mA]
V_{xy} [V]
A
B
C

FIG. 10

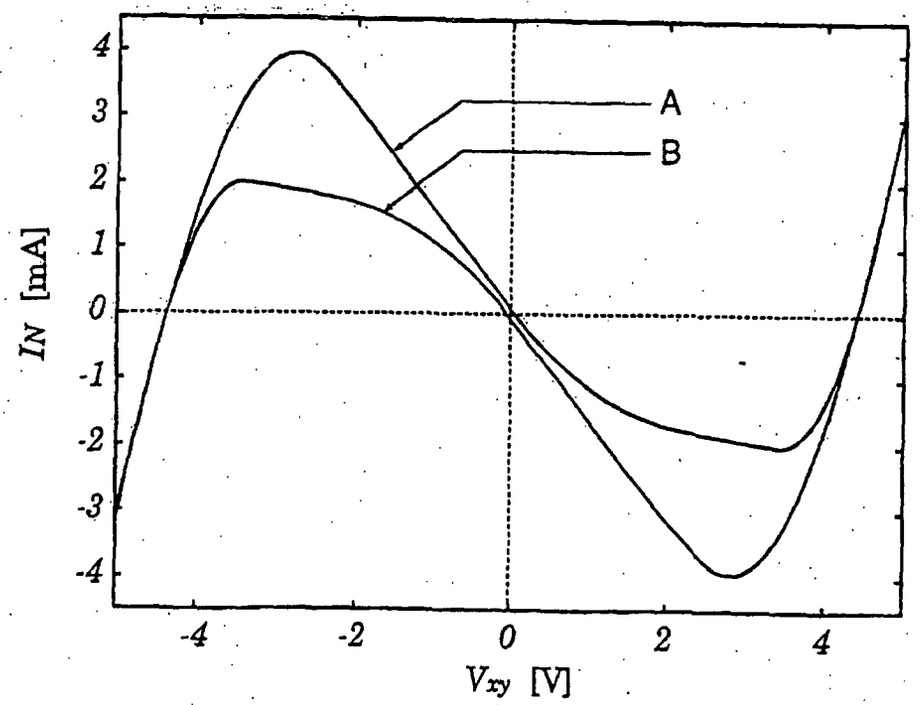

4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4
I_N [mA]
V_{xy} [V]
A
B

FIG. 11

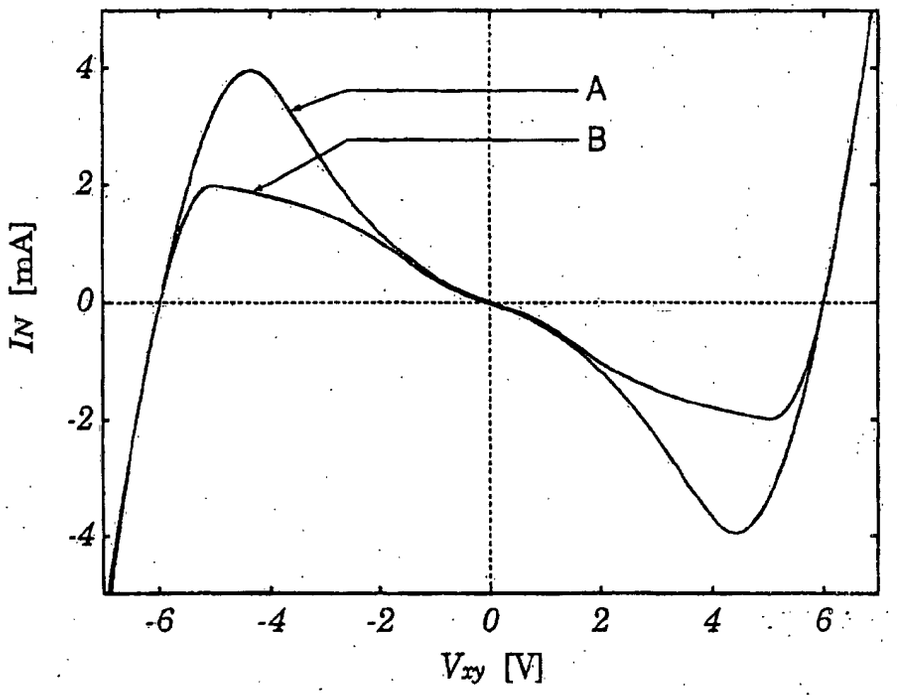


FIG. 12

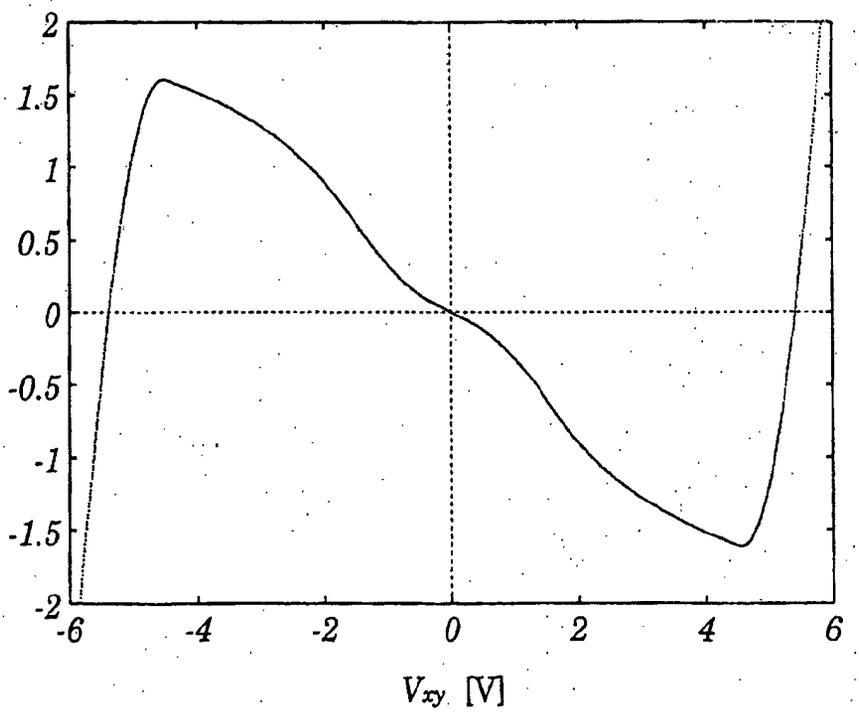


FIG. 13

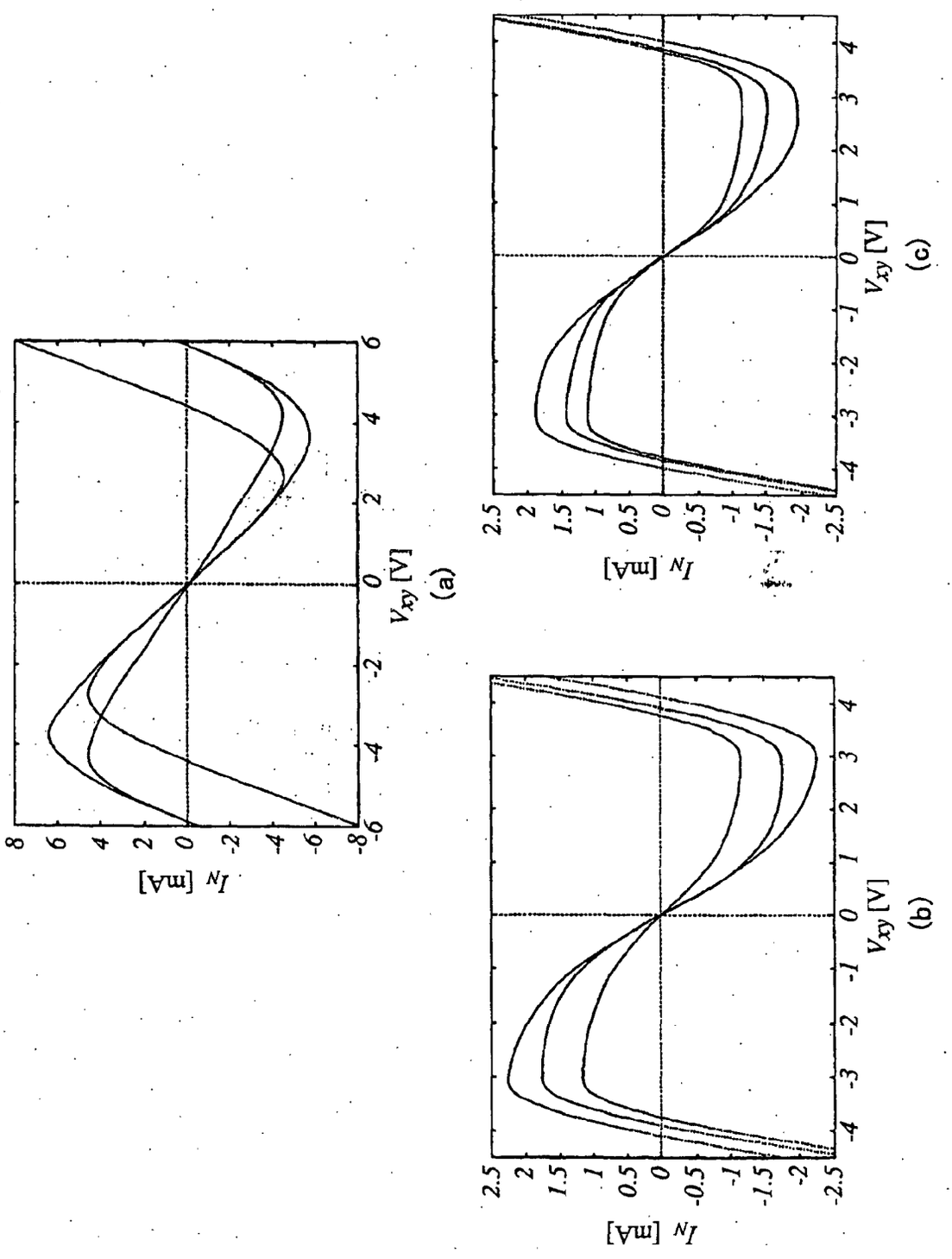


FIG. 14

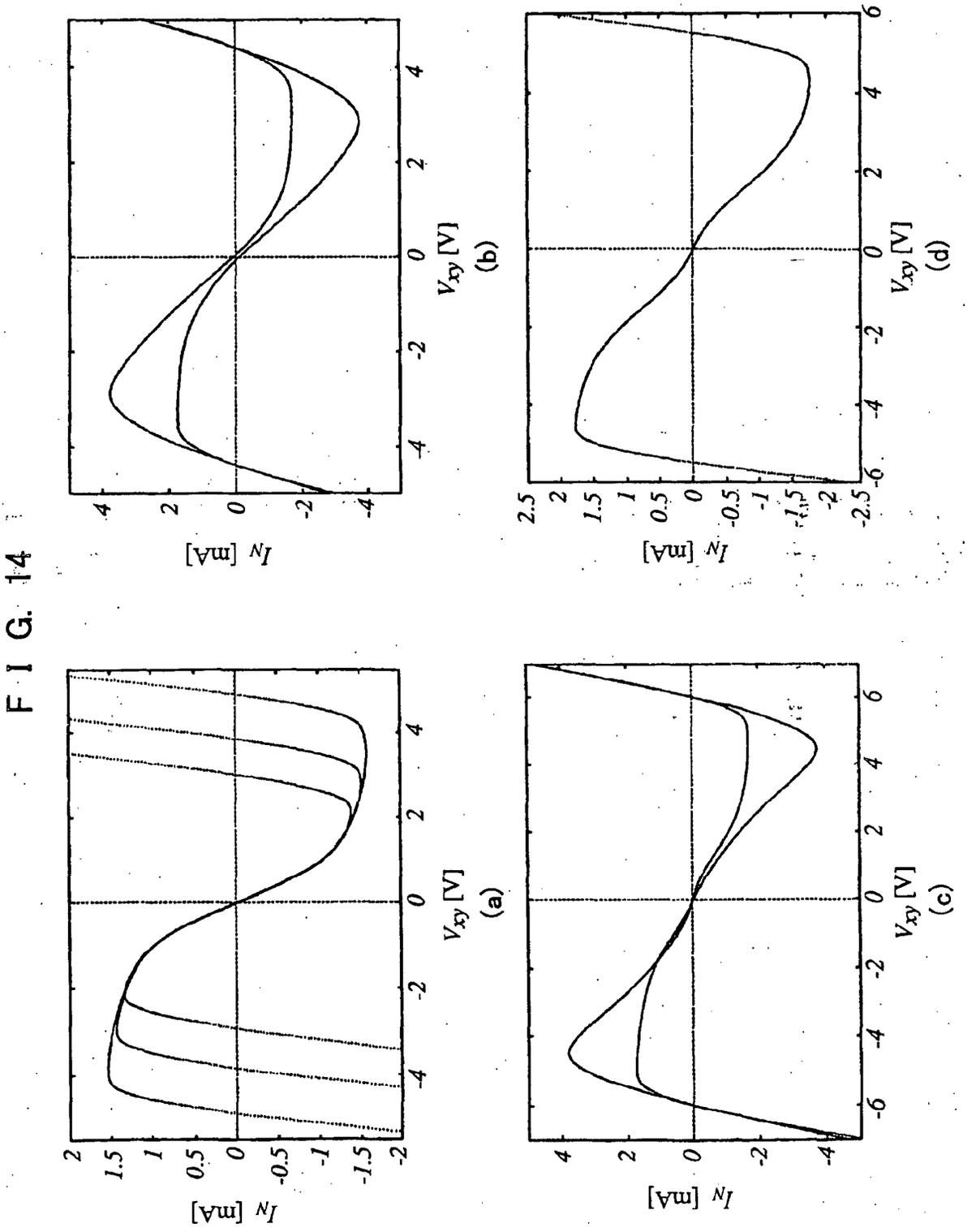


FIG. 15

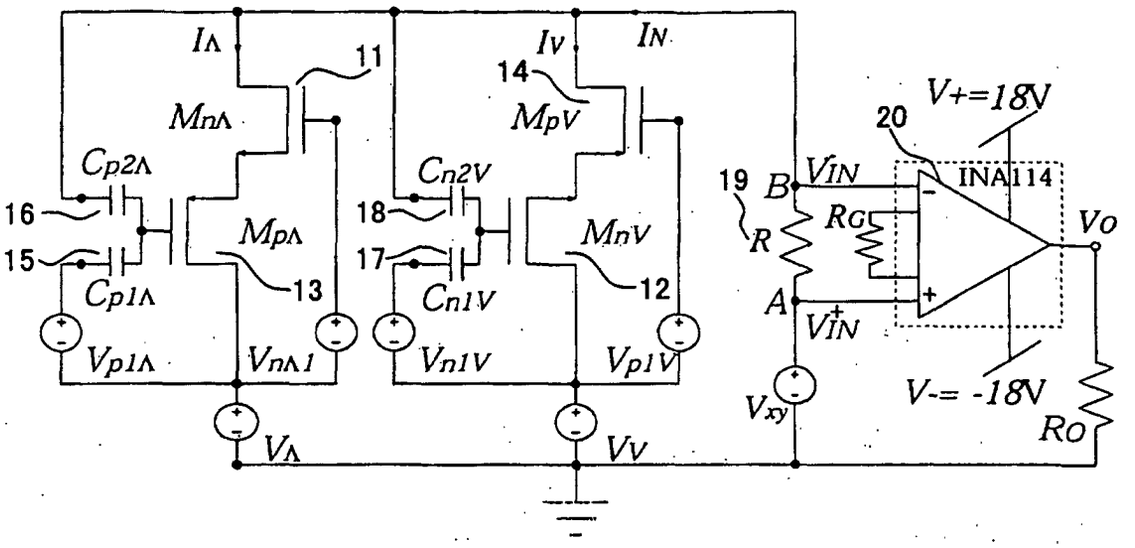

IΛ
11
IV
IN
14
MnΛ
MpV
V+=18V
20
Cp2Λ
Cn2V
19
B
VIN
INA114
16
18
MpΛ
MnV
RG
Vo
15
17
R
Cp1Λ
Cn1V
13
12
A
VIN
Vp1Λ
Vn1Λ
Vn1V
Vp1V
Vxy
V-= -18V
RO
VΛ
VV

FIG. 16

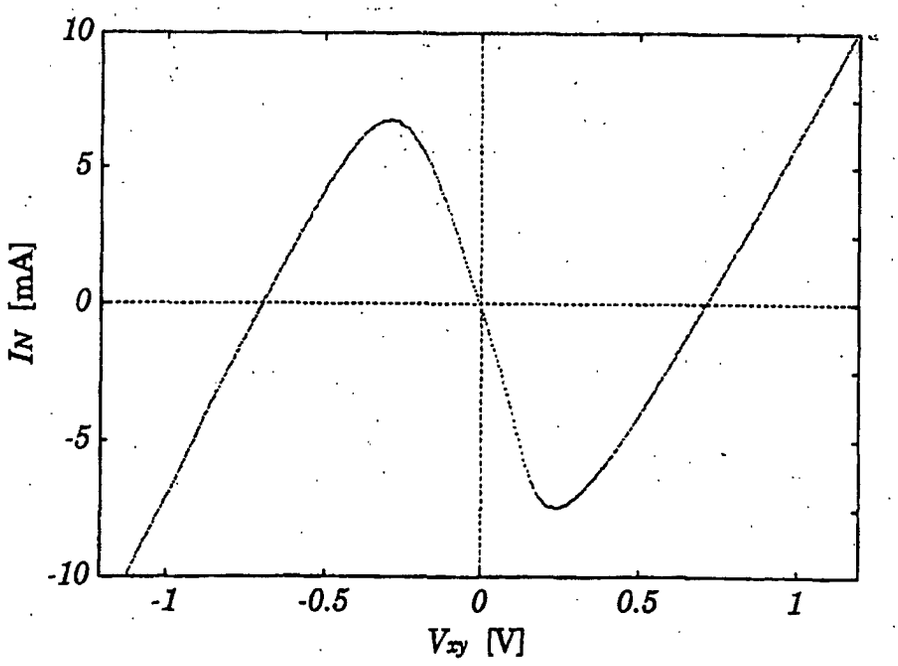

10
5
0
-5
-10
IN [mA]
-1
-0.5
0
0.5
1
Vxy [V]

FIG. 17

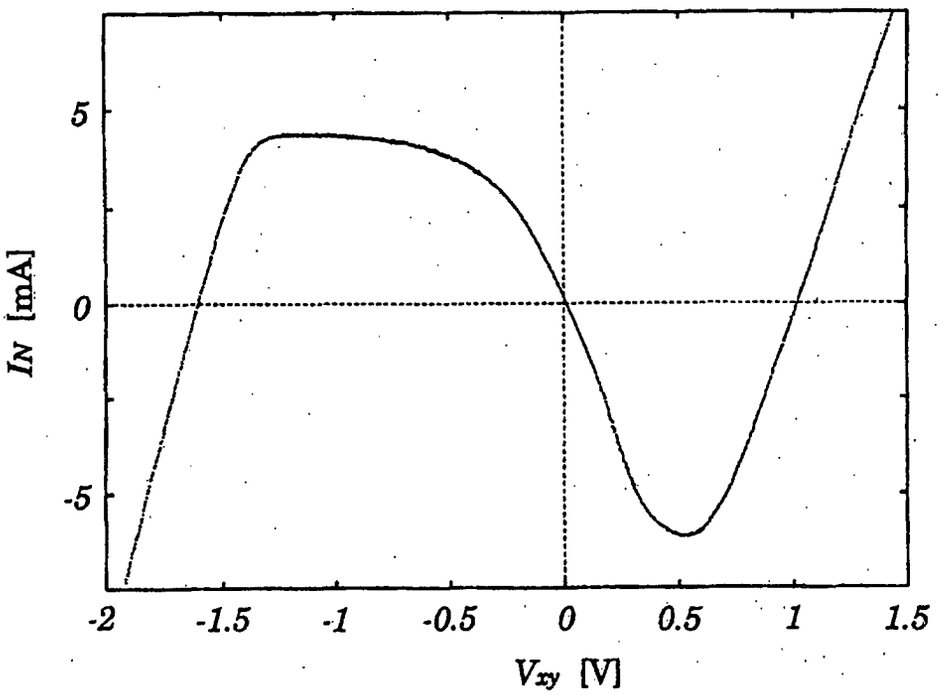


FIG. 18

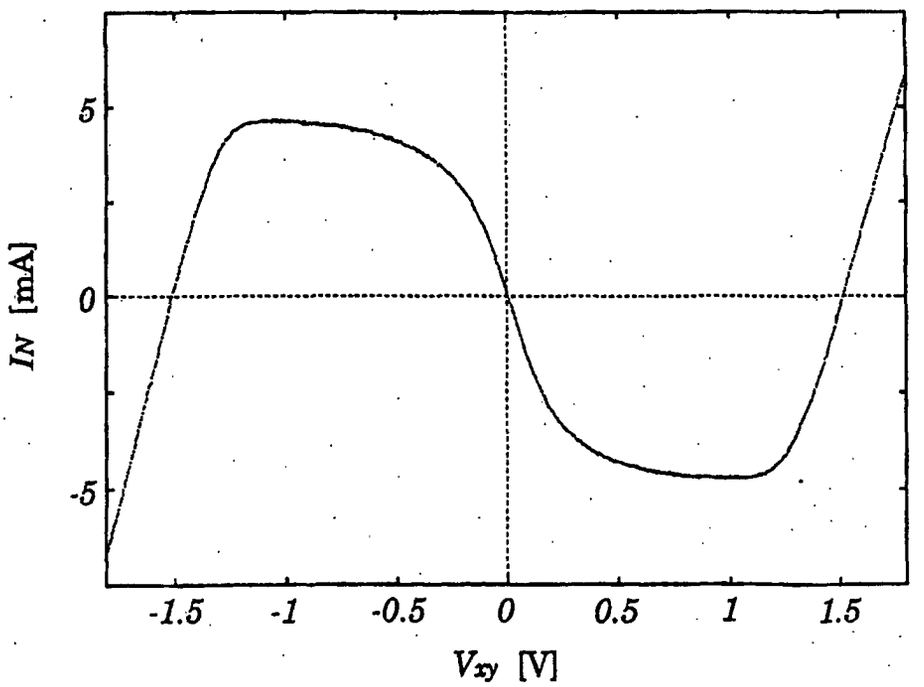


FIG. 19

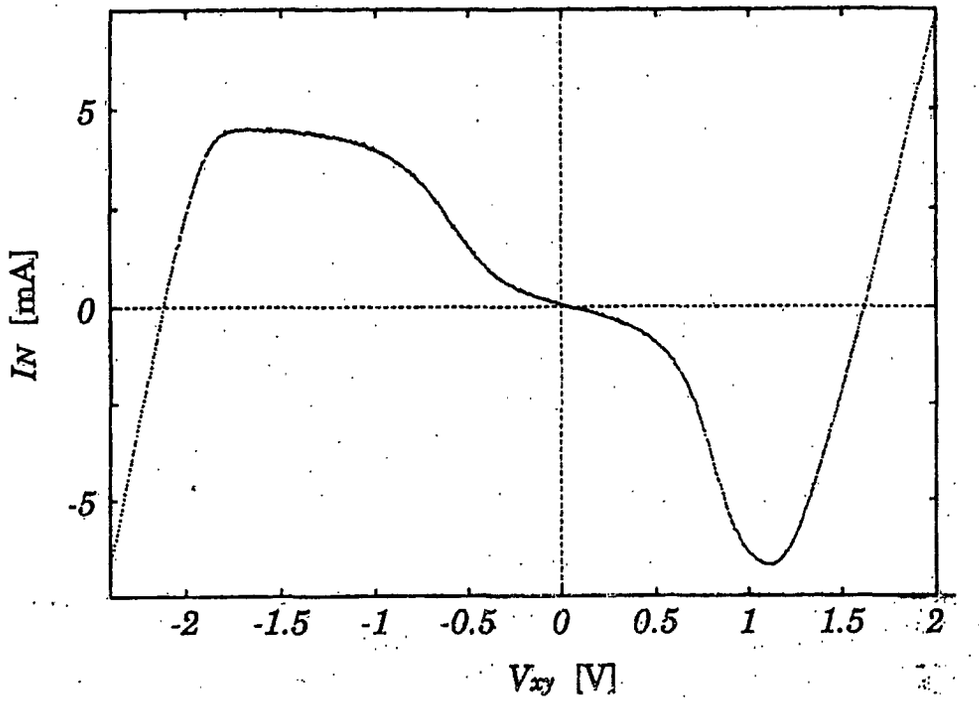
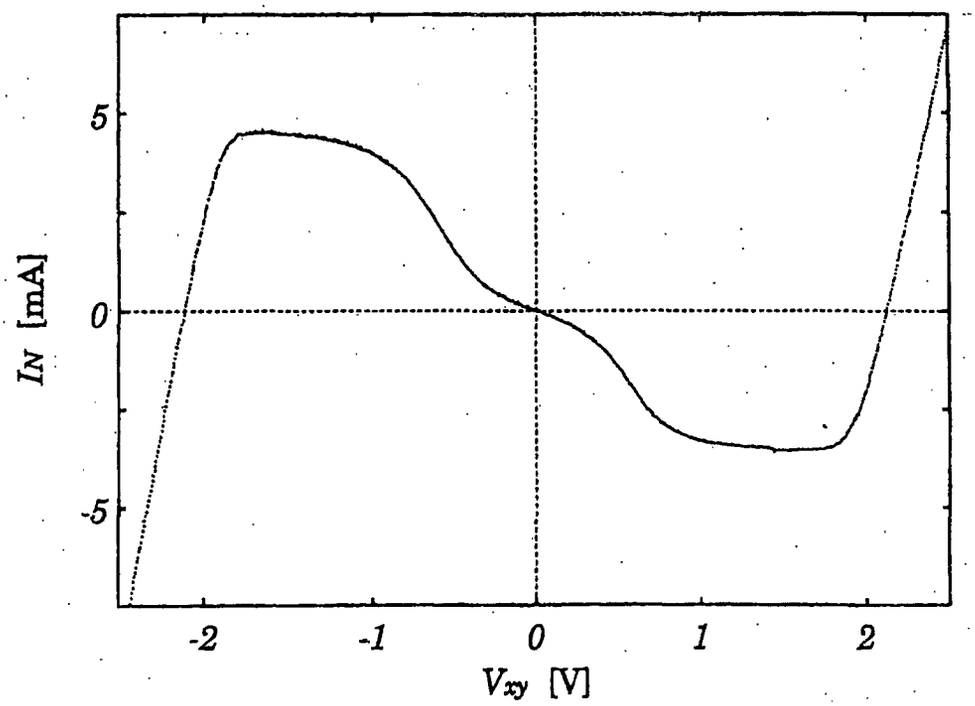


FIG. 20



F I G. 21

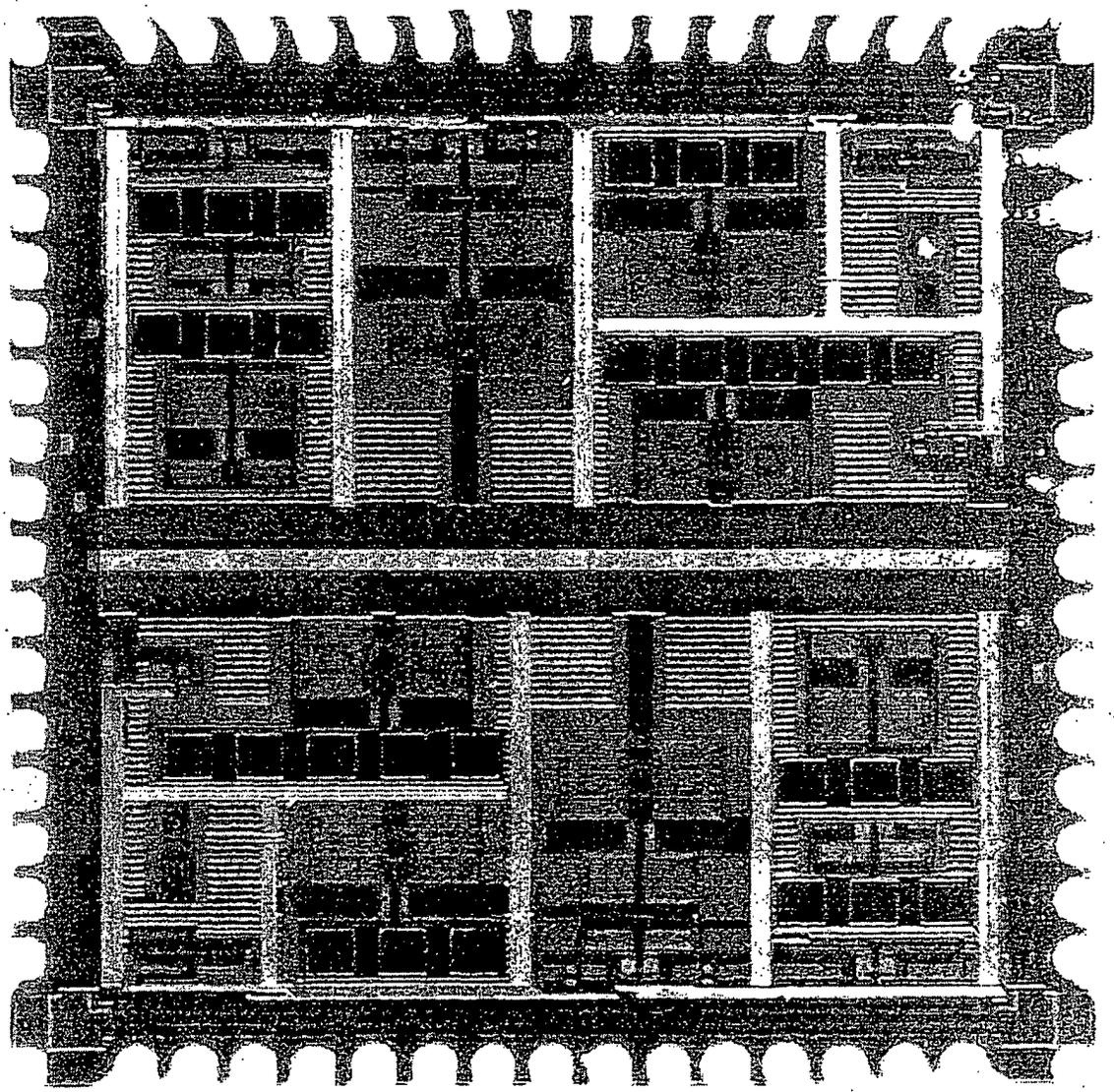


FIG. 22

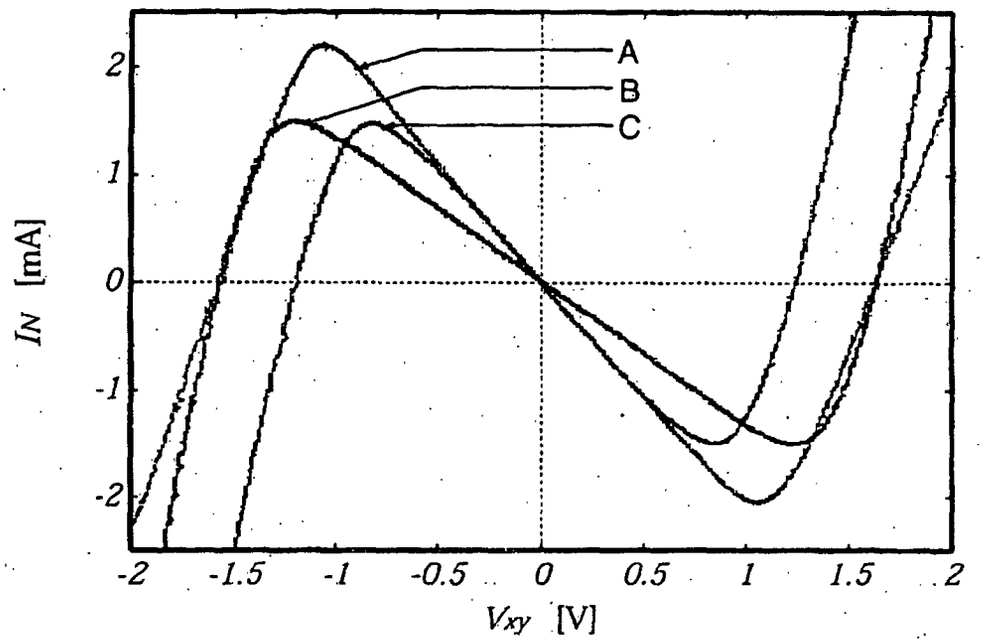

A
B
C
2
1
0
-1
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
I_N [mA]
V_{xy} [V]

FIG. 23

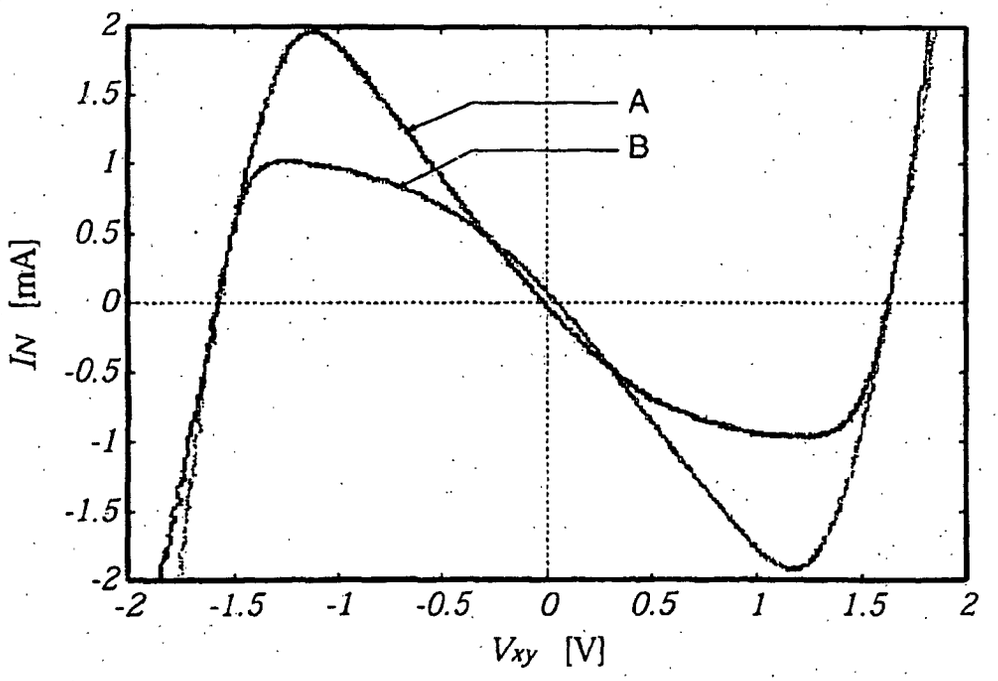

A
B
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
I_N [mA]
V_{xy} [V]

FIG. 24

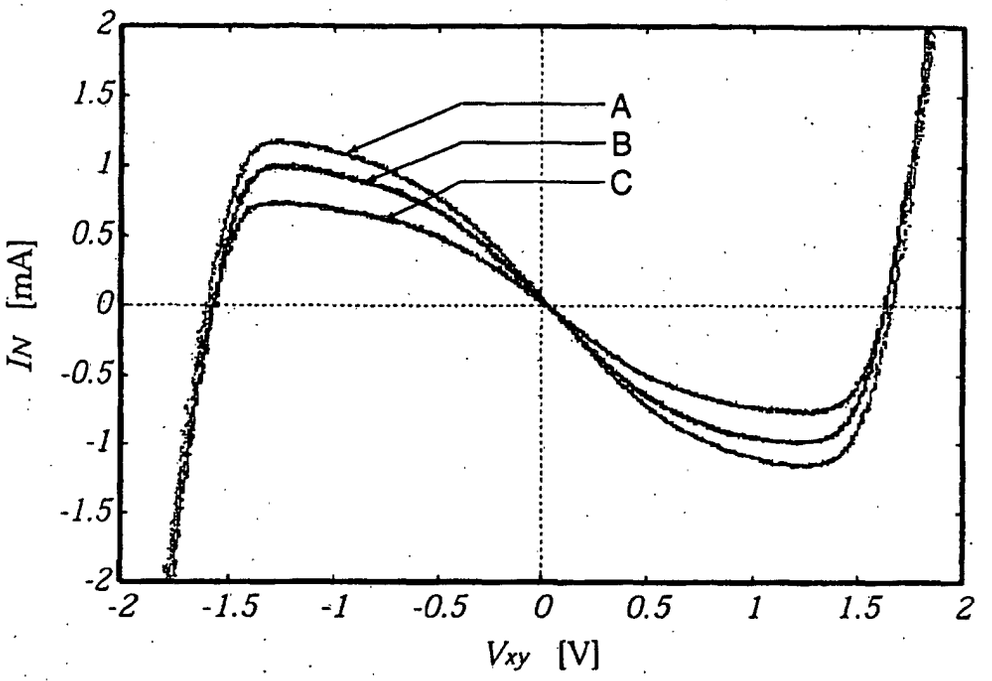

2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
A
B
C
I_N [mA]
V_{xy} [V]

FIG. 25

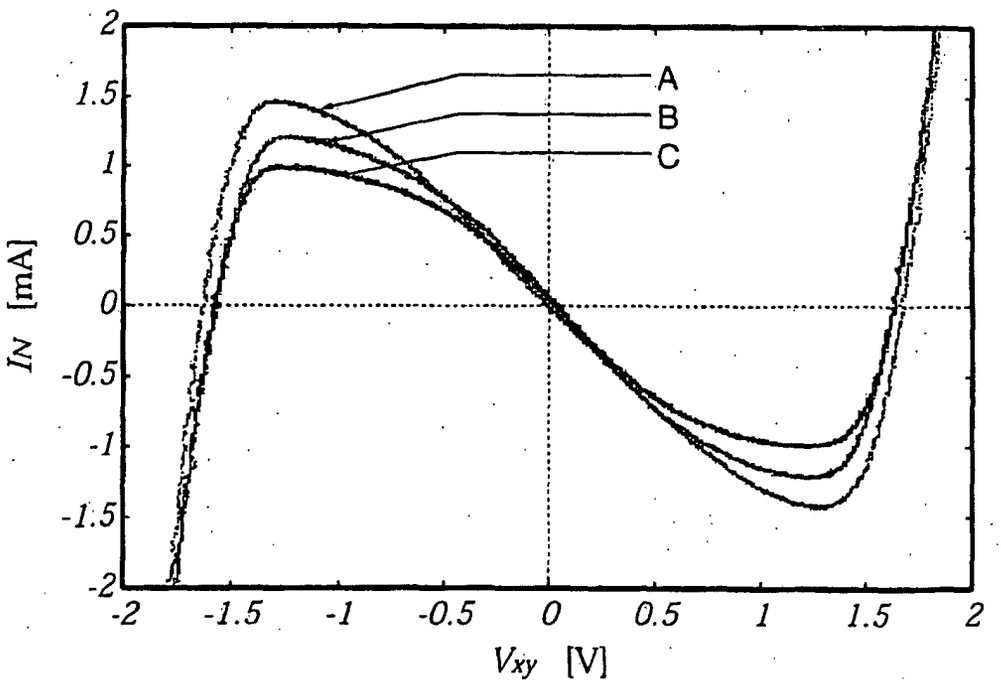

2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
A
B
C
I_N [mA]
V_{xy} [V]

FIG. 26

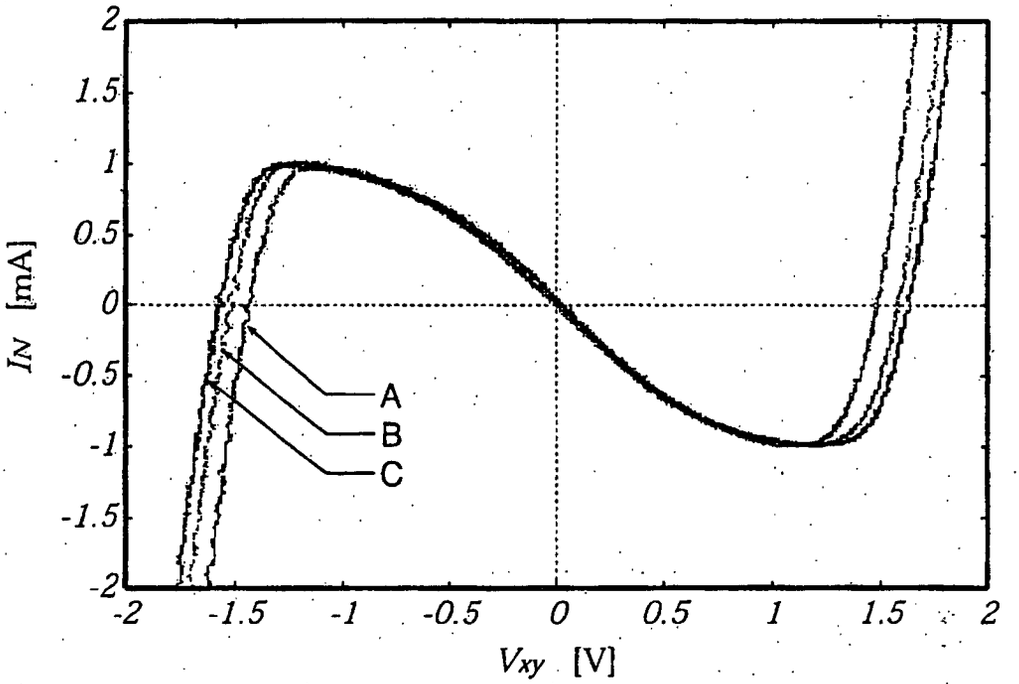
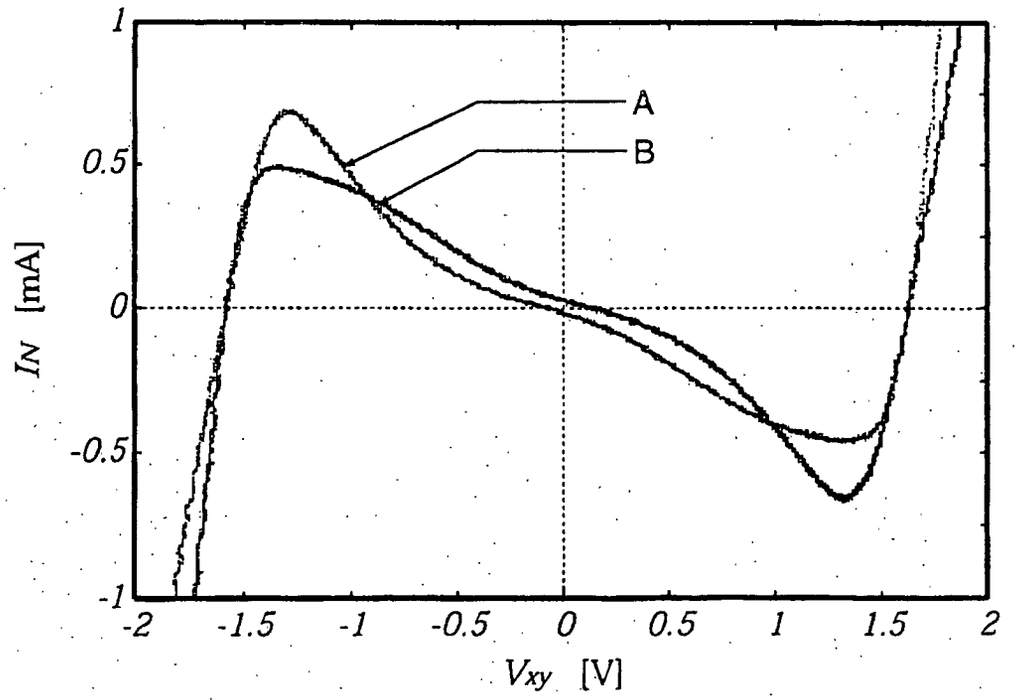
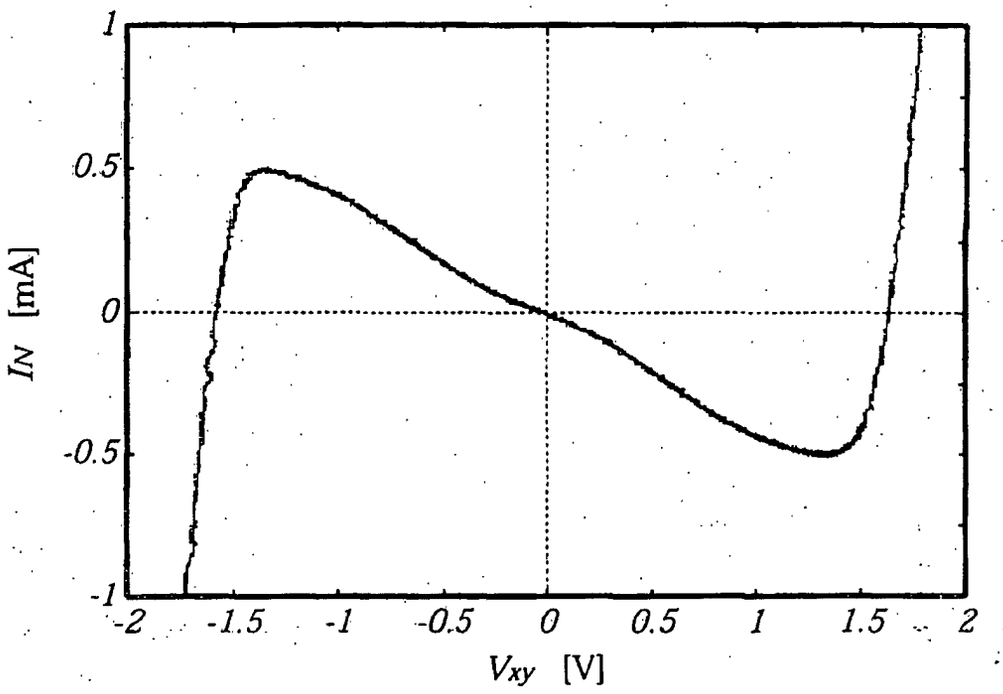

2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
I_N [mA]
A
B
C
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
V_{xy} [V]

FIG. 27


1
0.5
0
-0.5
-1
I_N [mA]
A
B
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
V_{xy} [V]

F I G. 28



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP03/00513

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl[7] H03H11/52

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
Int.Cl[7] H03H11/52

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Toroku Jitsuyo Shinan Koho	1994-2003
Kokai Jitsuyo Shinan Koho	1971-2003	Jitsuyo Shinan Toroku Koho	1996-2003

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A Y	JP 2000-68788 A (Japan Science and Technology Corp.), 03 March, 2000 (03.03.00), All pages; all drawings & US 6356136 B	4-13 1-3
Y	JP 39-3222 B (International Standard Electric Corp.), 28 March, 1964 (28.03.64), Page 8, right column, line 22 to page 9, right column, line 23; Figs. 7 to 10 (Family: none)	1-3

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
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"&" document member of the same patent family

Date of the actual completion of the international search 12 March, 2003 (12.03.03)	Date of mailing of the international search report 25 March, 2003 (25.03.03)
Name and mailing address of the ISA/ Japanese Patent Office Facsimile No.	Authorized officer Telephone No.

Form PCT/ISA/210 (second sheet) (July 1998)