HIGH SPEED, LOW COST BiCMOS PROCESS USING PROFILE ENGINEERING

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to semiconductors and, more particularly, to an improved process for making complementary metal oxide semiconductor (CMOS) compatible bipolar CMOS (BiCMOS) devices.

Discussion of Related Art

A BiCMOS circuit includes both bipolar and complementary metal oxide semiconductor (CMOS) transistors in the same circuit. BiCMOS circuits enjoy advantages of both bipolar circuits and CMOS circuits. Bipolar circuits may drive high capacitive loads and thus provide large circuit fan outs and operate at high speed. CMOS circuits are relatively small in size and consume less power than other technologies. A typical BiCMOS device uses the bipolar circuits as a push-pull current booster and the CMOS circuits as logic circuits and to drive the base current of the bipolar circuits.

Fig. 1 is a schematic diagram of an example of a BiCMOS logic circuit 50 operating as an inverter. A totem pole-type output buffer 52 comprises a pull-up NPN bipolar transistor Q1 and a pull-down NPN bipolar transistor Q2. The base of transistor Q2 is coupled to an output terminal of a CMOS inverter 54 comprising a PMOS FET Q3 and an NMOS FET Q4. PMOS FET Q3 supplies a base current to bipolar transistor Q1 so that the logic circuit outputs a high voltage (data "1"). NMOS FET Q4 pulls a base charge from bipolar transistor Q1 so that the logic circuit outputs a low voltage (data "0"). The base of pull-down NPN bipolar transistor Q2 is connected to the source of NMOS FET Q5, which is turned on or off by the potential at the node of bipolar transistors Q1, Q2.

Many BiCMOS fabrication techniques are complicated and cannot be fabricated in standard CMOS foundries. This makes BiCMOS designs difficult to implement for integrated circuit designers that rely on standard CMOS foundries.

This Sheet Has Been Replaced

THIS SHEET HAS BEEN REPLACED

Fig. 2 is a cross-sectional view of a triple well polysilicon emitter BiCMOS device 200, which may be fabricated in a standard CMOS foundry. This device includes a p-type substrate 202 on which an NPN bipolar transistor 204 and CMOS device 206 are formed. The CMOS device comprises an NMOS device 208 and a PMOS device 210. The NPN transistor 204 includes a collector defined in an n-type c-well 212, a p-type base region 214, and an n+ emitter 216 formed by doped polysilicon. The NPN transistor 204 also includes an n+ n-plug collector ring 218 which contacts the collector 212 and reduces series resistance.

The NMOS device 208 is formed in a p-well 220 defined in the p-type substrate 202 and includes n+ drain and source regions 222A, 222B, and a gate oxide layer 224 on which a doped polysilicon p-type gate 226 is formed.

The PMOS device 210 is formed in an n-well 230 and includes p+ drain and source regions 232A, 232B, and a gate oxide layer 234 on which a doped polysilicon n-type gate 236 is formed. A number of field oxide regions 240 are defined on the surface as isolation areas between devices.

A prior art method for manufacturing this BiCMOS device 200 is illustrated with reference to Figs. 3A - 3H. Fig. 3A shows a p-type substrate 202. The substrate may be a conventional p-type wafer having a resistivity of about 6 to 9 Ω cm^{-2}. A 310 nm thick sacrificial oxide layer 302 is formed on the substrate to provide a protective layer for formation of the n-plug.

The sacrificial oxide layer 302 is etched from the areas where the n-plug ring collector 218 is to be formed. A second etch, removing 120 nm silicon for the c-well lithography alignment, is also performed. The photoresist layer is stripped and the wafer is cleaned. The wafer is exposed to an oxidation step to grow a 20 nm thick screen oxide for the following implant steps. The n-plug ring is formed by an implant of arsenic at an energy of 150 keV and a dose of 1 x 10^{15} cm^{-3}. The result of these steps is illustrated in Fig. 3B.

Next, all of the oxide is stripped off of the wafer. A 30 nm stress release oxide (SRO) layer 304 is grown and then a 150 nm nitride layer 306 is deposited on the SRO layer by using low pressure chemical vapor deposition (LPCVD). These two layers are masked and the SRO and nitride layers 304, 306 are etched to create windows for forming the c-well 212. (These layers are also etched to create a window for the n-well 230 in the following step with the n-well

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

mask.) When the windows are provided, the c-well implant is performed using a conventional implant of phosphorus at an energy of 150 keV with a maximum dose of 3 x 10^{13} cm^{-3}. After the c-well and n-well implant, an n-well/c-well oxidation step is carried out at 1050°C to grow an oxide layer 307 of 4000Å. The result of these steps is shown in Fig. 3D.

Conventional CMOS steps follow: the nitride layer over the p-well is etched off and the p-well implant is carried out as the 3800Å n-well/c-well oxide protects the n-well/c-well from the implant. The oxide layer 307 is then removed. A CMOS p-well drive-in step is carried out at 1150° for 8 hours.

As seen in Fig. 3E, a number of field oxide regions (FOX) 240 are formed on the substrate 202. These FOX regions 240 may be formed in any well-known manner.

A gate oxide 234 is grown on the substrate surface in a conventional manner. Then, the gate oxide is etched off over the base area 214 to form a base window with a base mask. The result of these steps is shown in Fig. 3F.

Next, a base implant is performed using a p-type impurity such as BF_2 at an energy of 80 keV and a typical dose of 2 x 10^{13} cm^{-3}. This forms the p-type base 214. The wafer is cleaned and approximately 20Å of oxide is removed using a precise oxide HF in 50:1 HF for 10 sec to remove oxide from the base area before polysilicon deposition. The result of these steps is shown in Fig. 3G.

Next, polysilicon deposition is performed. The NMOS and PMOS polysilicon gate structures 226, 236 are located on the gate oxide; a polysilicon emitter 217 is located on the substrate surface, in contact with the p-type base 214. The polysilicon emitter 217 is doped with an extremely high arsenic implant. The dose is as high as 1 x 10^{16} cm^{-3} at an energy of 50 keV, which is four times higher than a conventional CMOS polysilicon implant. This high dose eliminates the two dimensional effect for the narrow emitter and provides high emitter concentration for high emitter injection. A shallow emitter drive-in step is performed. This drive-in results in a very shallow n+ layer 216 in the base area 214.

The next step is the polysilicon patterning with over-etch to remove polysilicon stringers along steps as well as etching away the n+ layer 216 in the extrinsic base region formed during the emitter drive-in step. A normal CMOS over-etch process is used because of the gate oxide beneath the polysilicon to protect the source and drain regions. But in this case, the bipolar base

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

part 214 is directly exposed to etching without oxide protection, so that a certain amount of silicon in the extrinsic base area is etched away. The result of these steps is shown in Fig. 3H.

Conventional CMOS steps follow including n-LDD, p-LDD, spacer formation, NMOS source and drain implant, and PMOS source and drain implant.

As noted above, this BICMOS device may be fabricated in many CMOS foundries without substantially changing the CMOS components. The c-well has a uniform profile. That is, the c-well has a dopant concentration which is highest near the substrate surface and which decreases as it deepens from the surface. The c-well is doped in this manner to improve frequency-current response by lowering the c-well sheet resistance (R_{sc}). However, lowering R_{sc} degrades the BV_{ceo} i.e., collector-emitter breakdown voltage breakdown. Thus, in this device, the optimum R_{sc} which may be achieved is 300 Ω/sq and, as a tradeoff, a 4V BV_{ceo} and a maximum f_T (cut off frequency) of 15 GHz. This is because a lower R_{sc} results in a higher f_T.

It is an object of the present invention to provide a CMOS compatible BiCMOS fabrication technique which increases f_T and maintains an acceptable BV_{ceo}.

SUMMARY OF THE INVENTION

This and other objects of the present invention are provided by a BiCMOS device having a c-well fabricated using profile engineering (a multi-energy implant using accurate dosages and energies determined by simulation) to provide a higher c-well implant dose while creating a narrow region with relatively low concentration in the collector depletion range to avoid low base-collector breakdown. This achieves a much lower collector series resistance to pull-up a frequency response, a collector sheet resistance which can be as low as 150 Ω/sq., f_T may be increased to 20 GHz or higher, and epitaxial wafers are avoided. This latter advantage is desirable because epitaxial wafers are incompatible with CMOS processes performed by most foundries.

The c-well may be formed using profile engineering so that the carrier concentration near the base-collector junction in the collector region is made lower than the dopant concentration in the deep region of the c-well. For example, the base-collector junction may be formed with a depth of 0.25 μm and have a regional (engineered) c-well carrier concentration less than 10^{17}

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

cm^{-3}; and the c-well may have a doping concentration higher than 10^{17} cm^{-3} at depths deeper than 0.6 μm.

Also, a method according to a preferred embodiment of the present invention eliminates a silicon etch step during the collector ring formation procedures to provide a more efficient method for creating a BiCMOS device than previously possible.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is described with reference to the following figures:

Fig. 1 is a schematic diagram of an example of a BiCMOS device logic circuit unit used as an inverter;

Fig. 2 is a cross sectional view of a prior art BiCMOS device;

Figs. 3A - 3H illustrate a conventional method for fabricating the BiCMOS device of Fig. 2;

Figs. 4A - 4H illustrate a method for fabricating a BiCMOS device according to the present invention;

Fig. 5 is a graph illustrating dopant concentration vs. distance from substrate surface in a prior-art c-well using three different dopant doses;

Fig. 6 is a graph illustrating dopant concentration vs. distance from substrate surface in a c-well according to the present invention;

Fig. 7 is a graph showing the concentrations of Fig. 6 for the depths between 0.0 and 1.0 μm from substrate surface; and

Fig. 8 is a linear scale of the graph of Fig. 7.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

To increase f_T while keeping BV_{ceo} at an acceptable level, the present invention provides a novel technology of precise profile engineering of the c-well. By using profile engineering in the c-well, a much higher c-well implant dose may be achieved, which provides a lower collector series resistance to pull up the frequency response. The profile engineering maintains a narrow region having a relatively low concentration in the collector depletion range which may be at a depth of, for example, from 0.2 μm to 0.5 μm, to avoid low base-collector breakdown. This allows the collector sheet resistance to be lowered down as low as 150 Ω/sq. The resultant

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

BiCMOS structure looks similar to the structure shown in Fig. 2, with the most significant difference being that the c-well concentrations are different, as described below. The present invention also eliminates a silicon etch step during the n-plug formation, and thus improves the morphology of the device.

A method for fabricating a BiCMOS device according to the present invention is described with reference to Figs. 4A - 4L. Fig. 4A shows a p-type substrate 202. The substrate is preferably a conventional p-type wafer having a resistivity of about 6 to 9 Ω/cm^{-2}. A stress release oxide (SRO) 408 is grown on the substrate 202. Preferably, the SRO 408 is 30nm thick. Next, a nitride layer 410 is deposited on the SRO. Preferably, the nitride layer 410 is 150nm thick and deposited using LPCVD. Using photolithographic methods, photoresist is placed on the nitride layer 410 to define a c-well window 404. The nitride layer 410 is etched off, keeping the SRO 408 as a screen for a phosphorous implant described below. The photoresist is kept on. Next, a c-well implantation is performed using, for example, phosphorus at an energy of 150 keV and a dose of between 3-5 x 10^{13} cm^{-3}, to form a c-well 212'. The photoresist is removed and the wafer is cleaned. The result of these steps is seen in Fig. 4A.

As seen in Fig. 4B, using photolithographic methods, a second mask is used to define an n-plug (collector ring) 218. When the n-plug windows are opened, the exposed windows are doped with an n+ impurity such as arsenic, preferably at an energy of 150 keV and a dose of about $1x10^{15}$ cm^{-3}. This n-well doping step results in a reduced collector contact series resistance. The mask is then removed. After the n-plug implant, a c-well drive in step is carried out, preferably at 1150°C for 8 hours or 1175°C for 200 minutes. The result of these steps is seen in Fig. 4B.

As seen in Fig. 4C, using photolithographic techniques, a third mask is used to define an n-well 412 window. The nitride layer 410 is removed for the n-well implant and LOCOS steps. The nitride layer 410 is preferably removed using a plasma etch. The n-well is created, for example, using an n-type impurity such as phosphorous. Preferably, this is done at an energy of 150 keV and a dose of $8x10^{12}$ cm^{-3}. The result of these steps is seen in Fig. 4C.

Next, the n-well/c-well LOCOS oxidation is performed to form a sacrificial LOCOS oxidation layer 414. This layer preferably has a thickness of 380 nm. Next, the remainder of the nitride layer 410 is removed, preferably using H_3PO_4 at 170°C for 60 minutes. Next, the

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

p-well implant is performed by implanting a p-type impurity, such as implanting boron at an energy of 50 keV and a dose of 4 x 10^{12} cm^{-3}. Next, a drive-in step is performed at 1150°C. This drive-in step finalizes the formation of the p-well 220 and the n-well 230. The result of these steps is seen in Fig. 4D.

Next, all the oxide is stripped to bare wafer in BOE and ready for the second nitride deposition. Note that after this step, the n-well and c-well areas 220, 212' are recessed about 160 nm below the p-well 220 plane. For simplicity, however, this is not shown in the figures. A second stress reduction oxide layer 416 is grown, preferably using dry oxidation at 900°C to create a 30 nm layer. A second nitride layer 418 is deposited using, for example, LPCVD to create a 150 nm layer. This second nitride layer 418 is etched to expose field oxide regions. The result of these steps is seen in Fig. 4E.

Next, a number of field oxide regions (FOX) 240 are formed on the substrate 202. These FOX regions may be formed in any well-known manner. The result of this step is seen in Fig. 4F.

Next a LOCOS field wet oxidation is performed. A nitride layer 418 is removed using, for example, H_3PO_4 at 170° for 60 minutes followed by an SRO HF dip off. The result of these steps is seen in Fig. 4F.

Next, optionally a V_t adjustment implant is performed to adjust the well doping to the desired V_t value. Next, a pre-gate oxide etch may be performed to clear active areas for gate oxidation.

Next, a gate oxide layer 430 is grown on the substrate surface in a conventional manner. Preferably, the gate oxide 430 has a thickness of 175Å + Δ, where Δ is an amount introduced to compensate for a HF dip thickness loss, discussed below. The gate oxide in the base active area is etched off over the c-well 212' area by lithography to form a window 432. This window is used to perform the collector profile engineering implants. The profile engineering uses one or more implants of a p-type dopant, such as boron, having predetermined dosages and energy levels precisely to control the total dopant concentration of the c-well 212'. Preferably, these implants are as follows:

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

Dopant	Energy	Dosage
Boron	65 keV	2.1×10^{12} cm^{-3}
Boron	120 keV	2.2×10^{12} cm^{-3}

These precisely engineered boron implants partially compensate the n-type phosphorous doping previously performed in the specified region.

The gate oxide over the base active area is etched away. The base is then doped to a p-type conductivity using, for example, boron at an energy of 20 keV and a dose of 2×10^{13} and 7°. This type of implant reduces channelling of implanted ions. This forms p-type base 214. The result of these steps is seen in Fig. 4G.

Next, an HF dip is performed to remove native oxide formed in base areas during photoresist stripping. This HF dip results in a small oxide loss Δ in the gate oxide 430. This thickness loss is Δ described above, which should be well controlled.

Next, polysilicon deposition is performed. The NMOS and PMOS polysilicon gate structures 226, 236 are located on the gate oxide (224, 234, respectively); a polysilicon emitter 216 is located on the substrate surface, in contact with the p+ base 214. Preferably, the polysilicon layer is 280 nm. The polysilicon emitter 216 is doped with an extremely high arsenic implant. The dose is as high as 2×10^{16} cm^{-3} at an energy of 50 keV. The implant is annealed and a shallow emitter drive-in step is performed. This drive-in also results in a thin n+ layer 216A in the extrinsic base area which will be etched away by a precise over-etch of the polysilicon. The result of these steps is seen in Fig. 4H. The same steps may also form a top capacitor plate for the PMOS device capacitor.

Conventional CMOS steps follow to complete the fabrication of the inventive BiCMOS device. These conventional steps include n-LDD, p-LDD, spacer formation, NMOS source and drain implants, and PMOS source and drain implants. These steps are well known to those skilled in the art and are not further described.

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

Fig. 5 is a graph 500 of a simulated profile of three c-well implants without using profile engineering, such as in the prior art device described below. The dosages are 3 x 10^{13} (line 502), 5 x 10^{13} (line 504), and 7 x 10^{13} (line 506), respectively. (Note that these last two dosages cannot be applied without proper profile engineering, but for purposes of this simulation, it is assumed that they can be.) Note that in all three incidences, between 0 and 1 μm from the substrate surface, the doping concentration is between 1 x 10^{17} and 5 x 10^{17}. Thus, a very high dopant concentration in the c-well 212 occurs near the substrate surface.

Figs. 6 and 7 illustrate the advantage of profile engineering in the present invention. Fig. 6 is a graph 600 illustrating the simulated c-well profile of a c-well 212' using profile engineering according to the present invention. Fig. 7 is a graph 700 showing the same concentration for depths between 0 and 1 μm from the substrate surface. These graphs show the concentration of arsenic 606 (from the emitter 216A), phosphorus 604 (from the c-well 212'), boron 608 (the base), and total effective dopant concentration 602 as a function of the distance from a surface of the substrate. Note that the emitter-base junction X_{JB}, preferably occurs at 0.09 μm from the substrate surface and has a concentration of about 2x10^{20} cm-3. The base-collector junction X_{JB}, preferably occurs at approximately 0.22 μm collector total and has a concentration less than 10^{17} cm^{-3} near the base-emitter junction. The engineered low concentration collector region preferably extends from 0.22 μm to approximately 0.55 μm. This region is important to collector-emitter breakdown after profile engineering. The total average concentration is about 8x10^{16}, which is much lower than the original level of 2.5x10^{17}. This lower concentration region allows for a much thicker depletion layer for higher breakdown. On the other hand, this low concentration region is very limited around the base-collector junction and has a thickness of only about 5% of the collector well. The high concentration of the collector well can increase f_T. At depths below 0.6 μm, the effective total dopant concentration may be as high as 2.5 x 10^{17} cm^{-3}. It is this precise profile engineering which permits a high total concentration in the c-well, yet a low concentration near the substrate surface.

Fig. 8 is a graph 800 showing the data of Fig. 7 plotted on a linear scale for a dosage of 7 x 10^{13} (line 804) and a dosage of 5 x 10^{13} (line 802). Note the low total concentration in the collector depletion region from approximately 0.1 μm to 0.4 μm from the substrate surface.

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

Using profile engineering in the manner described above permits the c-well to be formed so that the dopant concentration in the emitter-base junction, base-collector junction, and collector region which is lower than a dopant concentration in other regions of the c-well. The base-collector junction may be formed at about 0.25 μm and have a dopant concentration less than 10^{17} cm^{-3}; and the c-well may have a dopant concentration greater than 2.5 x 10^{17} cm^{-3} at depths deeper than 0.6 μm.

Disclosed is a BiCMOS device which provides a low collector series resistance without compromising the base-collector breakdown. This is achieved by using profile engineering to create a low carrier concentration at the base-collector junction, and collector region; yet providing a c-well having a very high overall concentration, thus lower R_{SC}. This achieves a much lower collector series resistance to pull-up a frequency response, a collector sheet resistance which can be as low as 150 Ω/sq., and f_T may be increased to 20 GHz or higher.

The above described embodiments of the invention are intended to be illustrative only. Numerous alternative embodiments may be devised by those skilled in the art without departing from the spirit and scope of the following claims.

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

* C L M S *

We claim:

1. A method for fabricating a bipolar complementary metal oxide semiconductor (BiCMOS), the method comprising the steps of:

a. forming in a substrate having a first conductivity type a complementary metal oxide semiconductor device, comprising an n-type metal oxide semiconductor device formed in a p-type well and a p-type metal oxide semiconductor device formed in a n-type well;

b. forming a bipolar transistor having a base, an emitter, and a collector, the transistor being formed in a c-well having a second conductivity type opposite the first conductivity type; and

c. forming the c-well using profile engineering so that a dopant concentration in a base-collector junction and a collector region is lower than a dopant concentration in other regions of the c-well.

2. The method of claim 1, wherein the step of forming the c-well further includes the steps of:

a. forming the base-emitter junction having a highly doped n+ polysilicon emitter, having a dopant concentration about 2×10^{20} cm^{-3};

b. forming the base-collector junction at about 0.25 μm and having a collector total concentration less than 10^{17} cm^{-3} near the base-emitter junction; and

c. the c-well having a dopant concentration greater than 10^{17} cm^{-3} at depths greater than 0.6 μm.

3. The method of claim 1, wherein the step of forming the c-well further includes the steps of:

a. forming in the substrate a c-well area by implanting first impurities having the second conductivity type;

b. forming in the substrate a collector ring by implanting second impurities having the second conductivity type; and

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

* C L M S *

c. performing profile engineering on the c-well by implanting third impurities having the first conductivity type using predetermined dosages and energy levels.

4. The method of claim 3, further comprising selecting the first impurities to be phosphorous atoms, selecting the second impurities to be arsenic atoms, and selecting the third impurities to be boron atoms.

5. A method for fabricating a bipolar complementary metal oxide semiconductor on a substrate having a first conductivity type, the method comprising the steps of:

a. growing an oxide layer on a surface of the substrate;

b. depositing on the oxide layer a nitride layer;

c. removing first selected portions of the nitride layer to expose a collector well window;

d. doping the collector well window with first impurities to a second conductivity type to form a collector well;

e. exposing a second selected portion of the substrate within the collector well to expose an n-plug collector ring window;

f. doping with a high concentration of second impurities to the second conductivity the second selected portions to form an n-plug collector ring;

g. forming complementary oxide semiconductor devices on the substrate;

h. growing a gate oxide on active areas of the substrate surface;

i. exposing a third selected portion of the gate oxide to expose the collector well;

j. using profile engineering, doping the collector well with third impurities of the first conductivity type at predetermined energy levels and dosages;

k. forming above the collector well a base region having the first conductivity type; and

l. depositing polysilicon above the base region and doping the polysilicon to the second conductivity type to form an emitter.

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

ABSTRACT

A bipolar complementary metal oxide semiconductor device has a c-well fabricated using profile engineering (a multi-energy implant using accurate dosages and energies determined by advance simulation) to provide a higher c-well implant dose while creating a narrow region with relatively low concentration in the collector depletion range to avoid low base-collector breakdown. This achieves a much lower collector series resistance to pull-up a frequency response, a collector sheet resistance which can be as low as 150 Ω/sq., and f_T may be increased to 20 GHz or higher.

This Sheet Has Been Replaced

THIS SHEET HAS BEEN REPLACED

This Sheet Has Been Replaced

FIG. 1
(PRIOR ART)

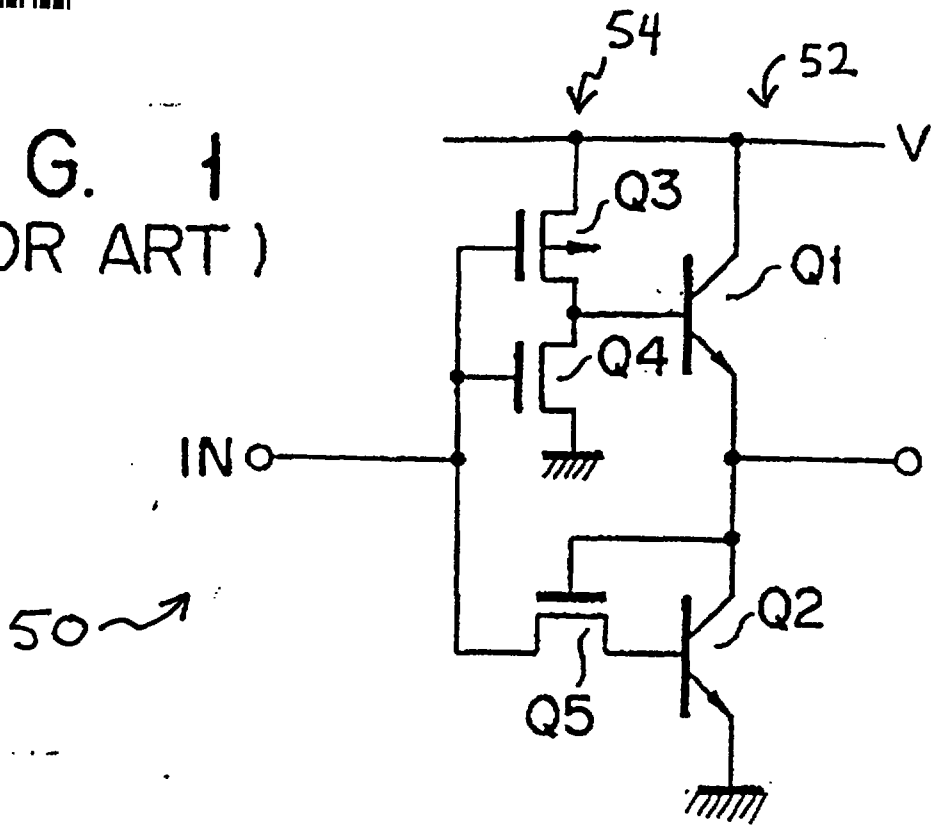
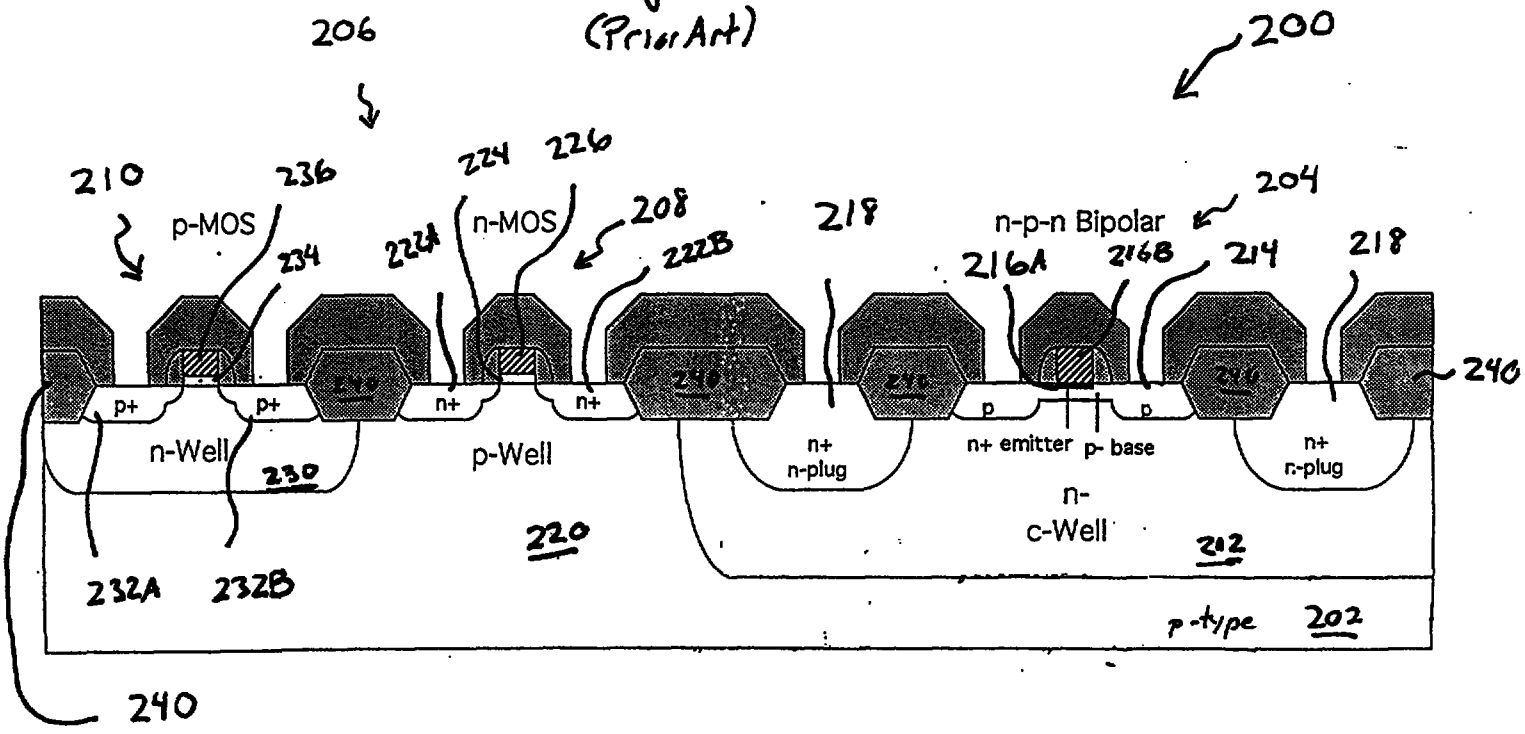


Fig. 2
(Prior Art)



THIS SHEET HAS BEEN REPLACED

Fig. 3A
(Prior Art)

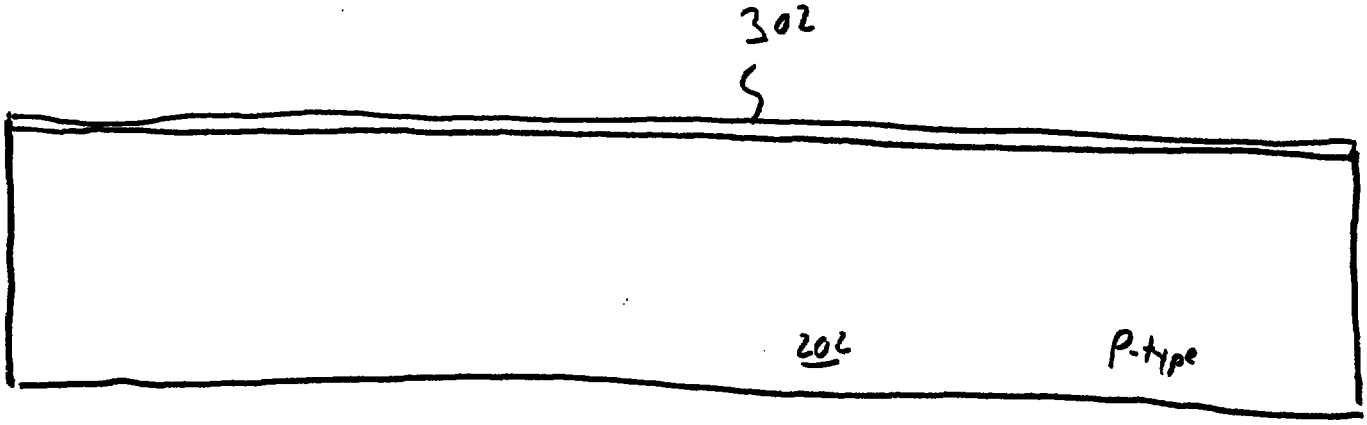
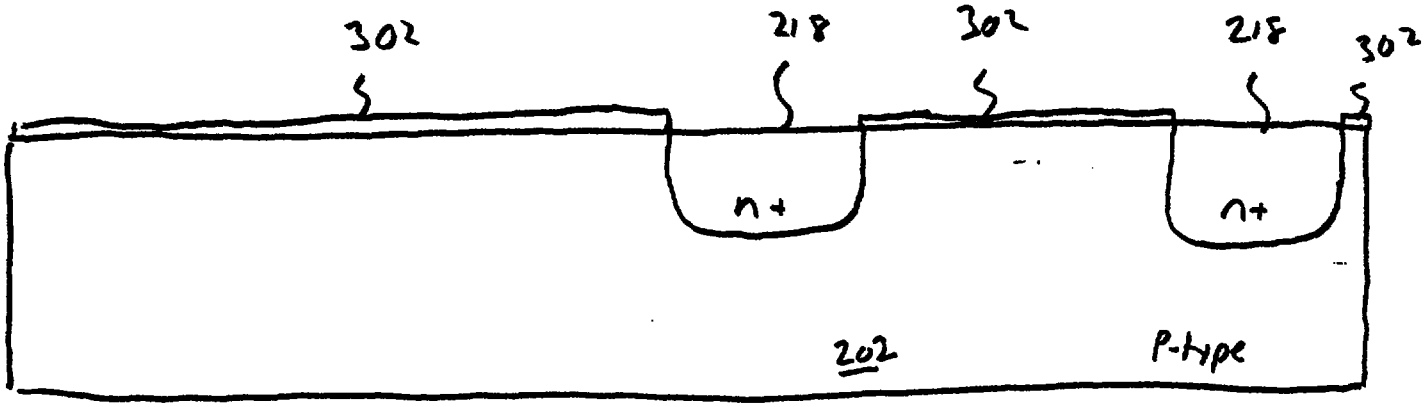


Fig. 3B
(Prior Art)



This Sheet Has Been Replaced

THIS SHEET HAS BEEN REPLACED

Fig. 3C
(Prior Art)

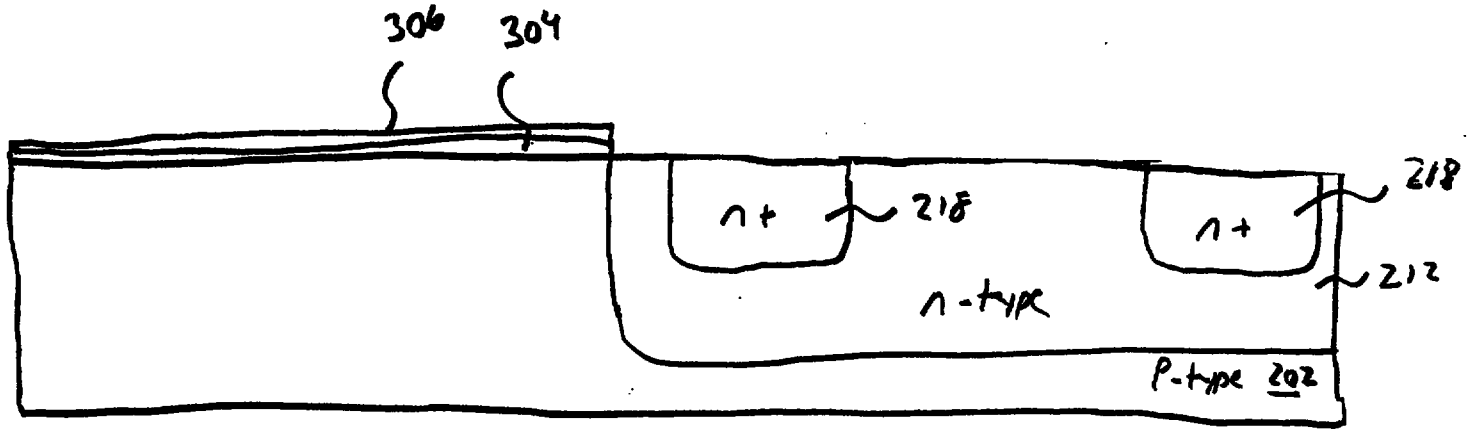


Fig. 3D
(Prior Art)

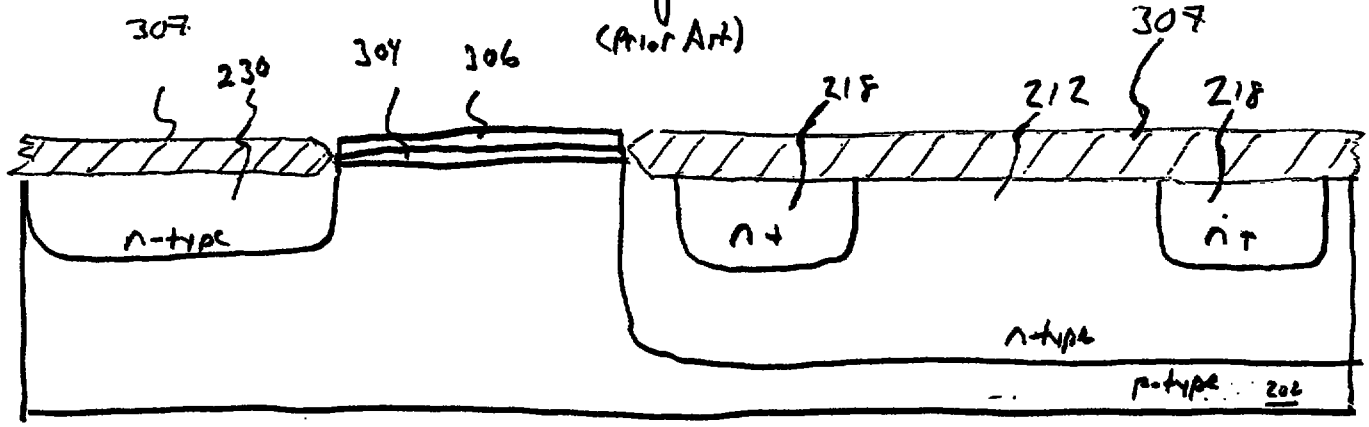
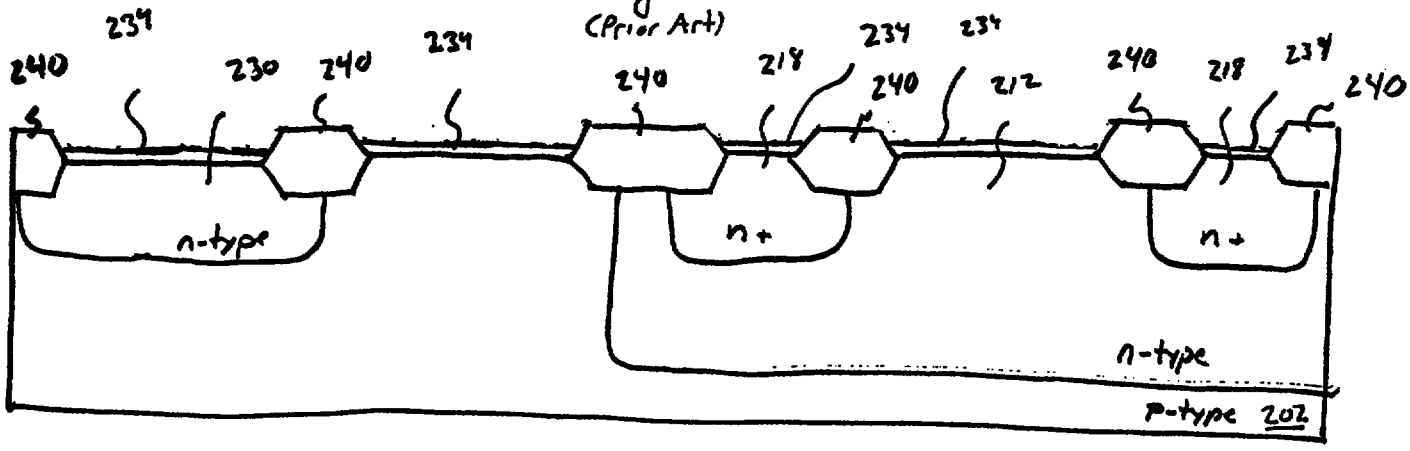


Fig. 3E
(Prior Art)



This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

Fig. 3F
(Prior Art)

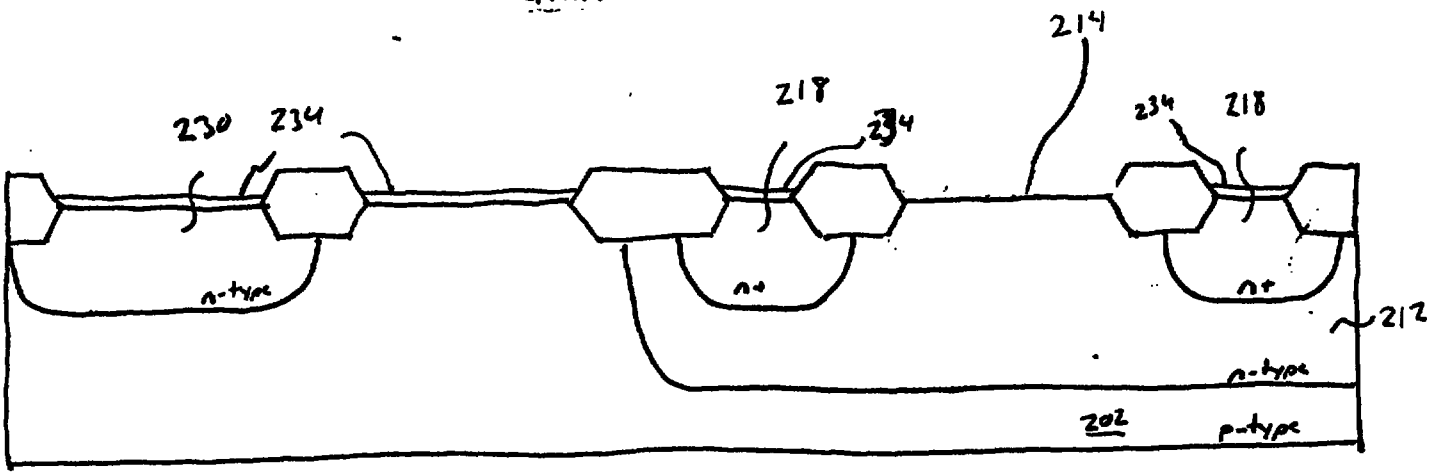


Fig. 3G
(Prior Art)

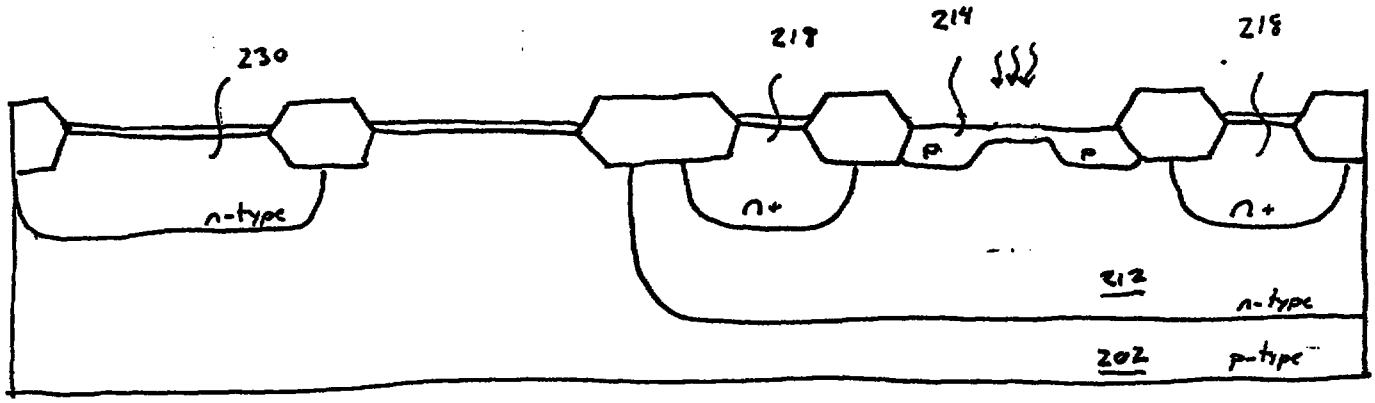
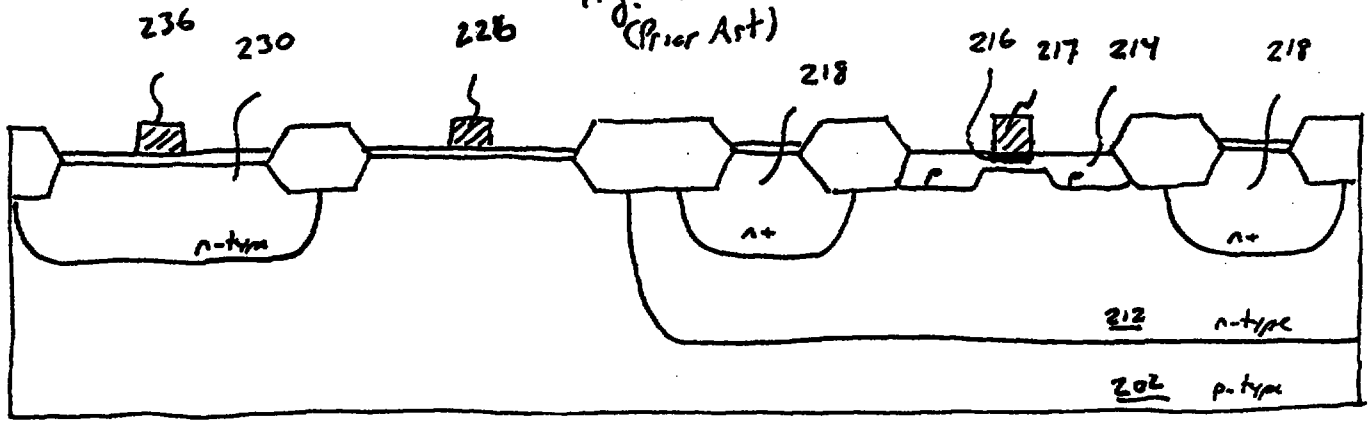


Fig. 3H
(Prior Art)



This Sheet Has Been Replaced

THIS SHEET HAS BEEN REPLACED

Fig. 4A

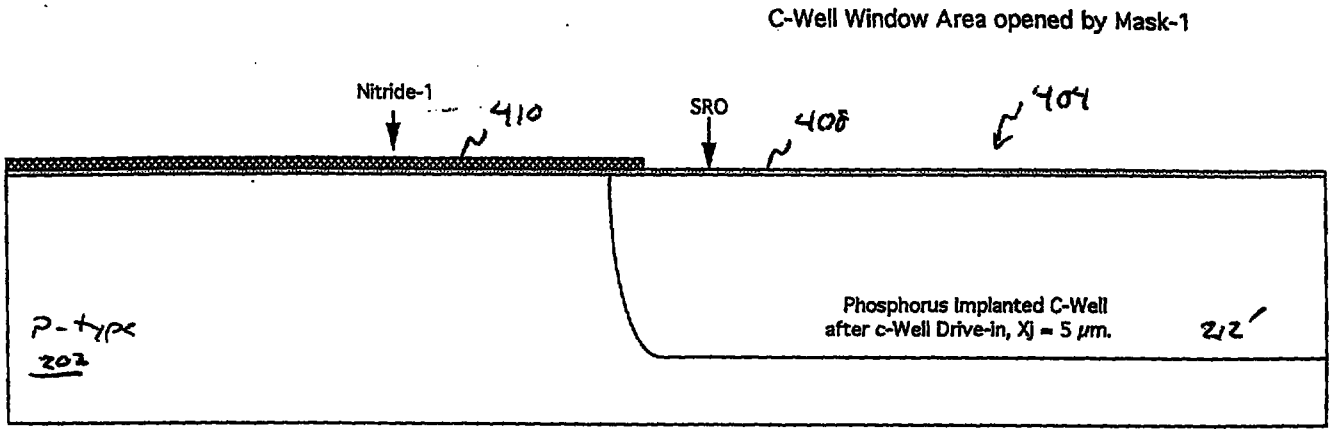


Fig. 4B

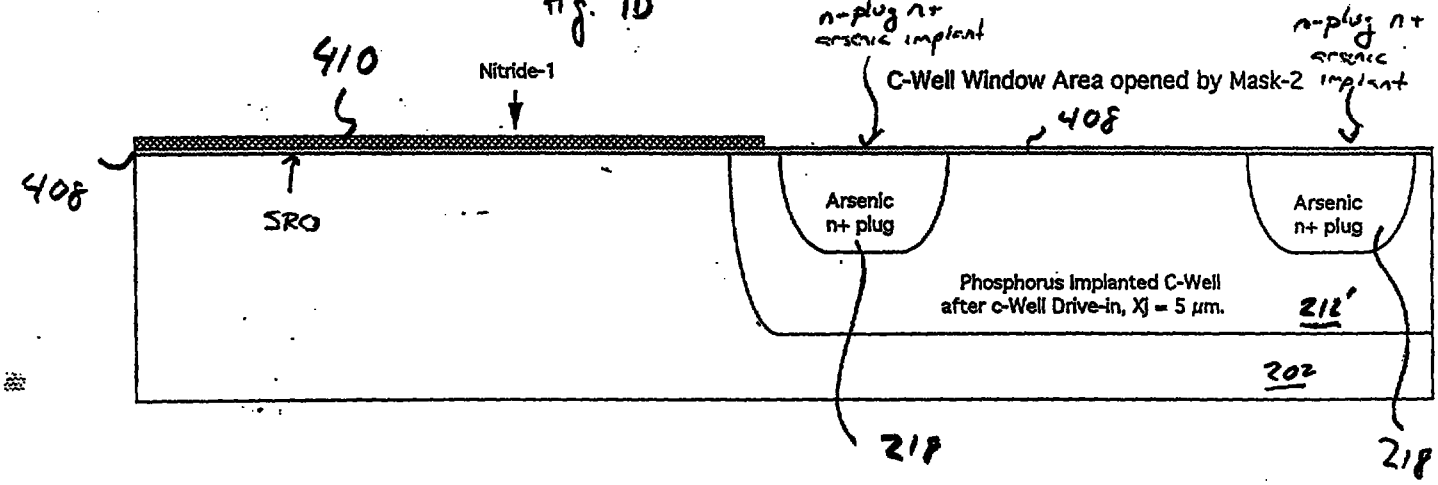
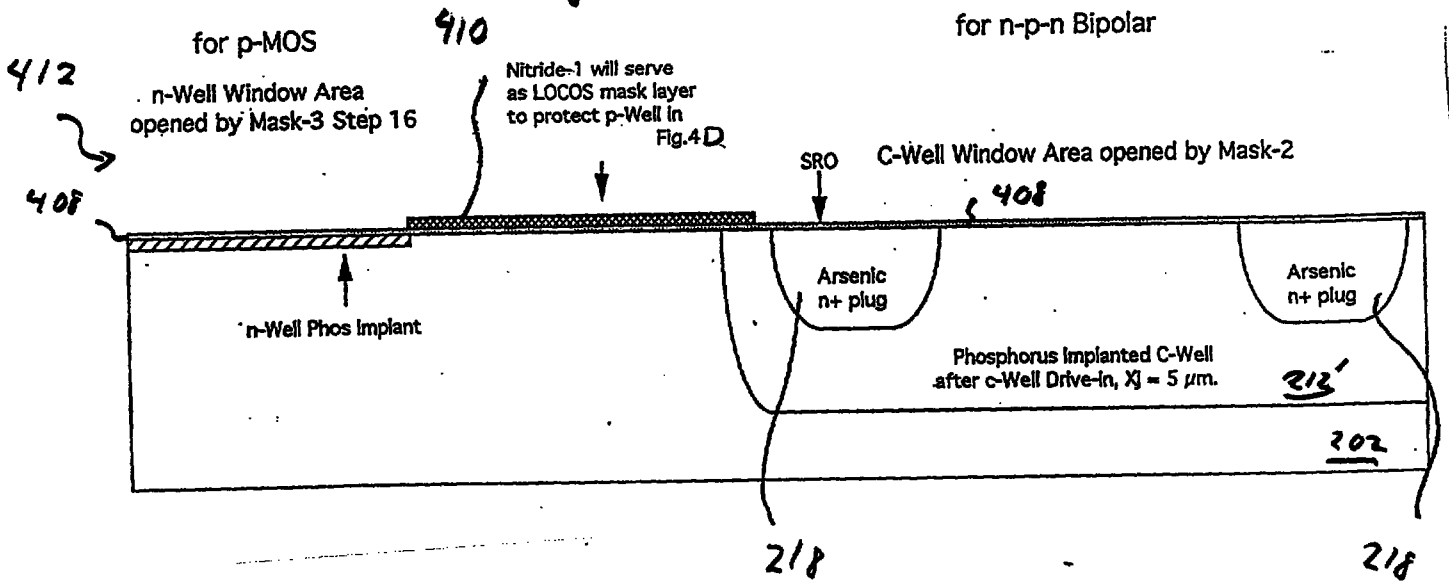


Fig. 4C



This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

Fig 4D

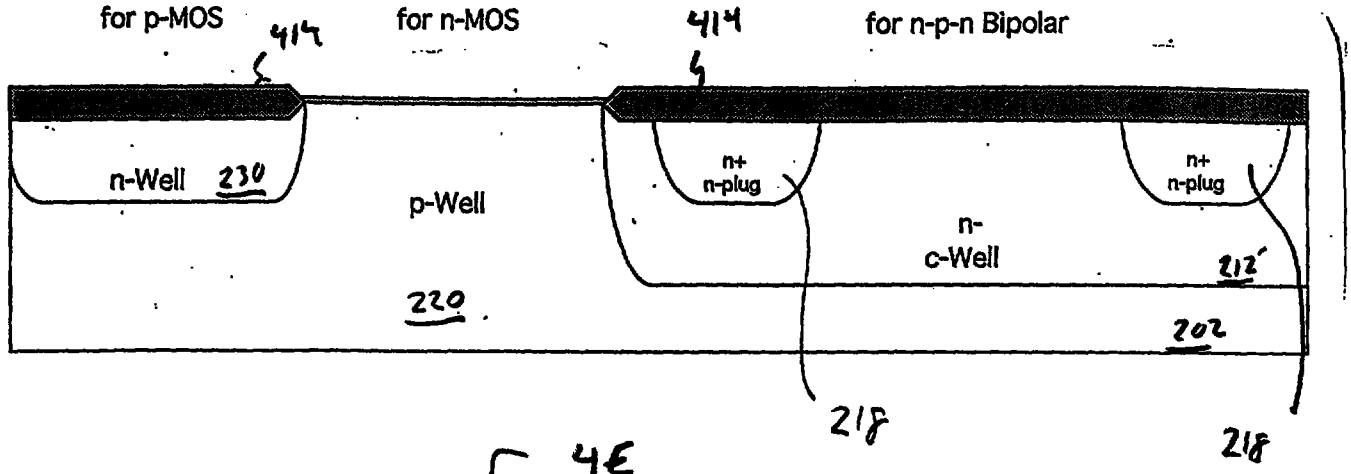


Fig. 4E

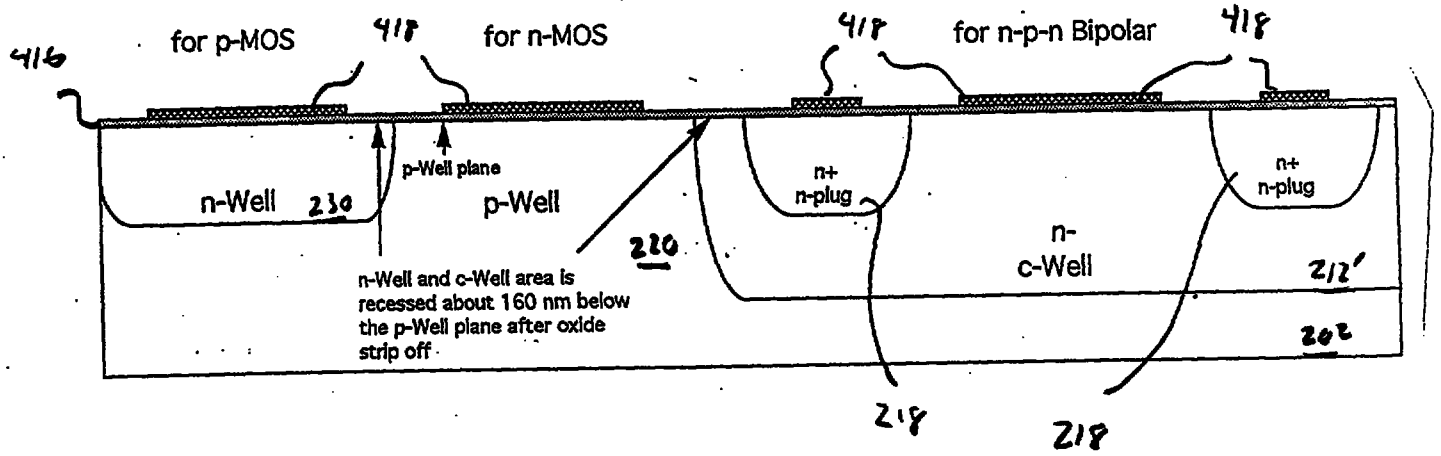
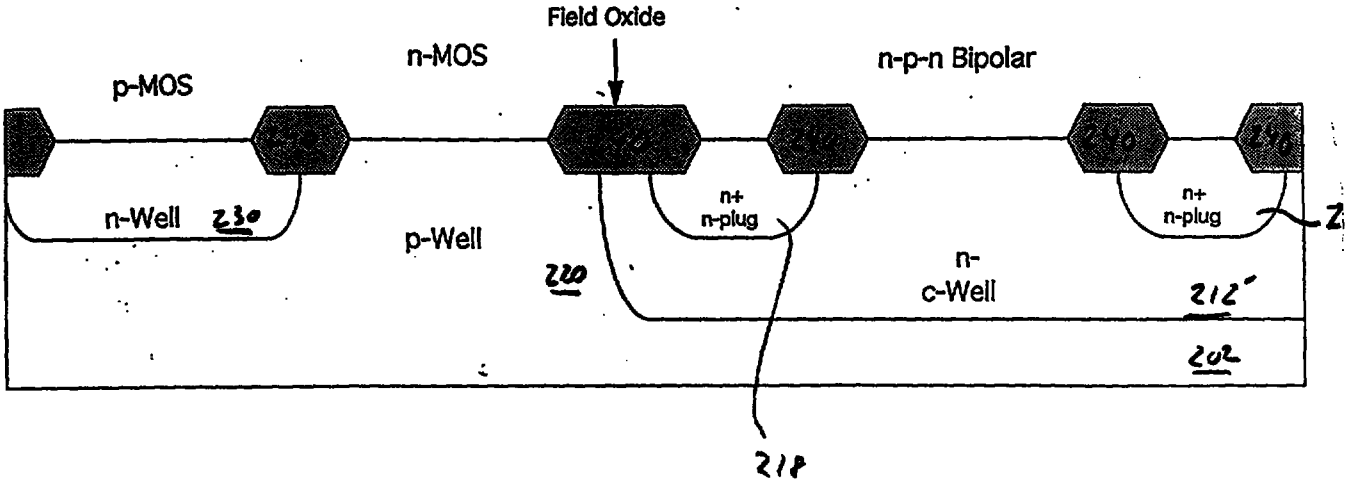


Fig. 4F



This Sheet Has Been Replaced

THIS SHEET HAS BEEN REPLACED

This Sheet Has Been Replaced

Fig. 4G

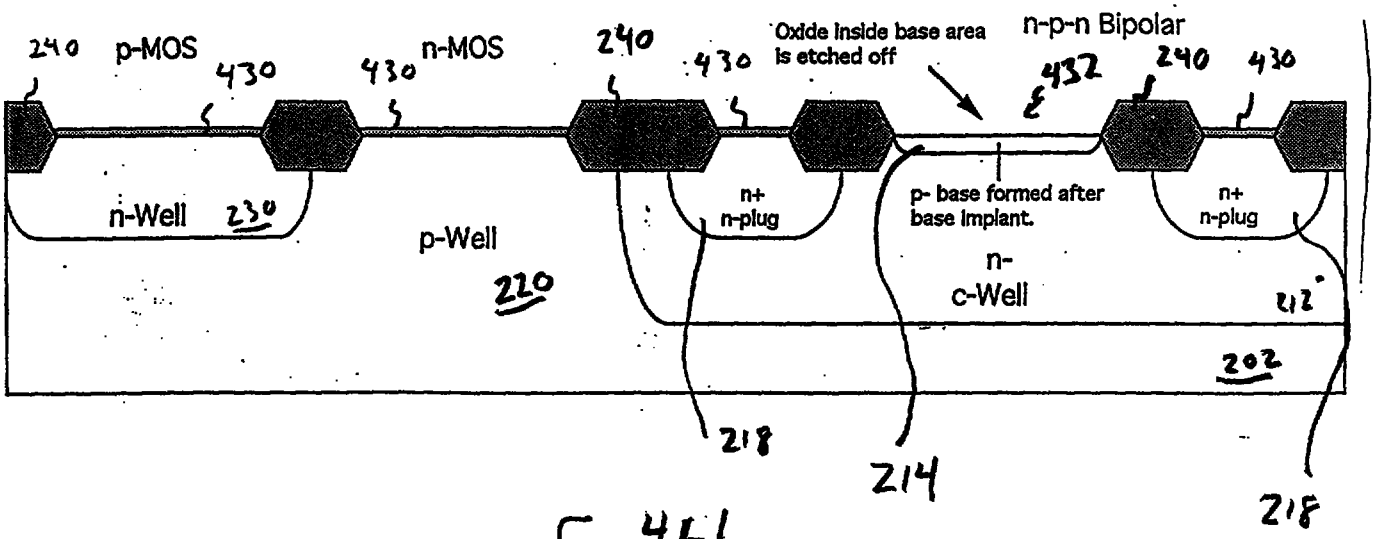
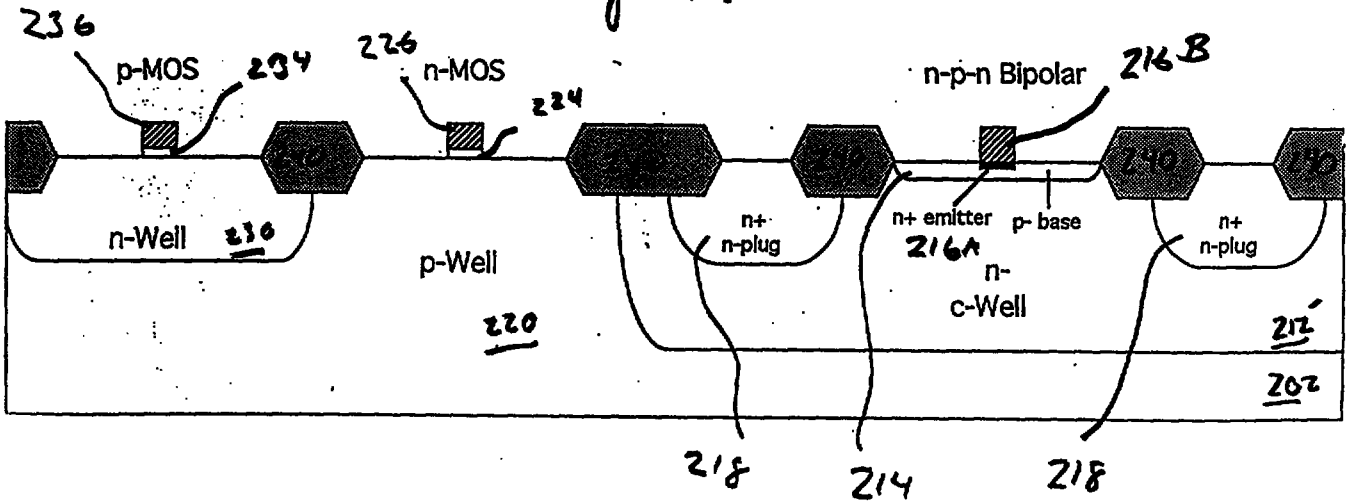


Fig. 4H



THIS SHEET HAS BEEN
REPLACED

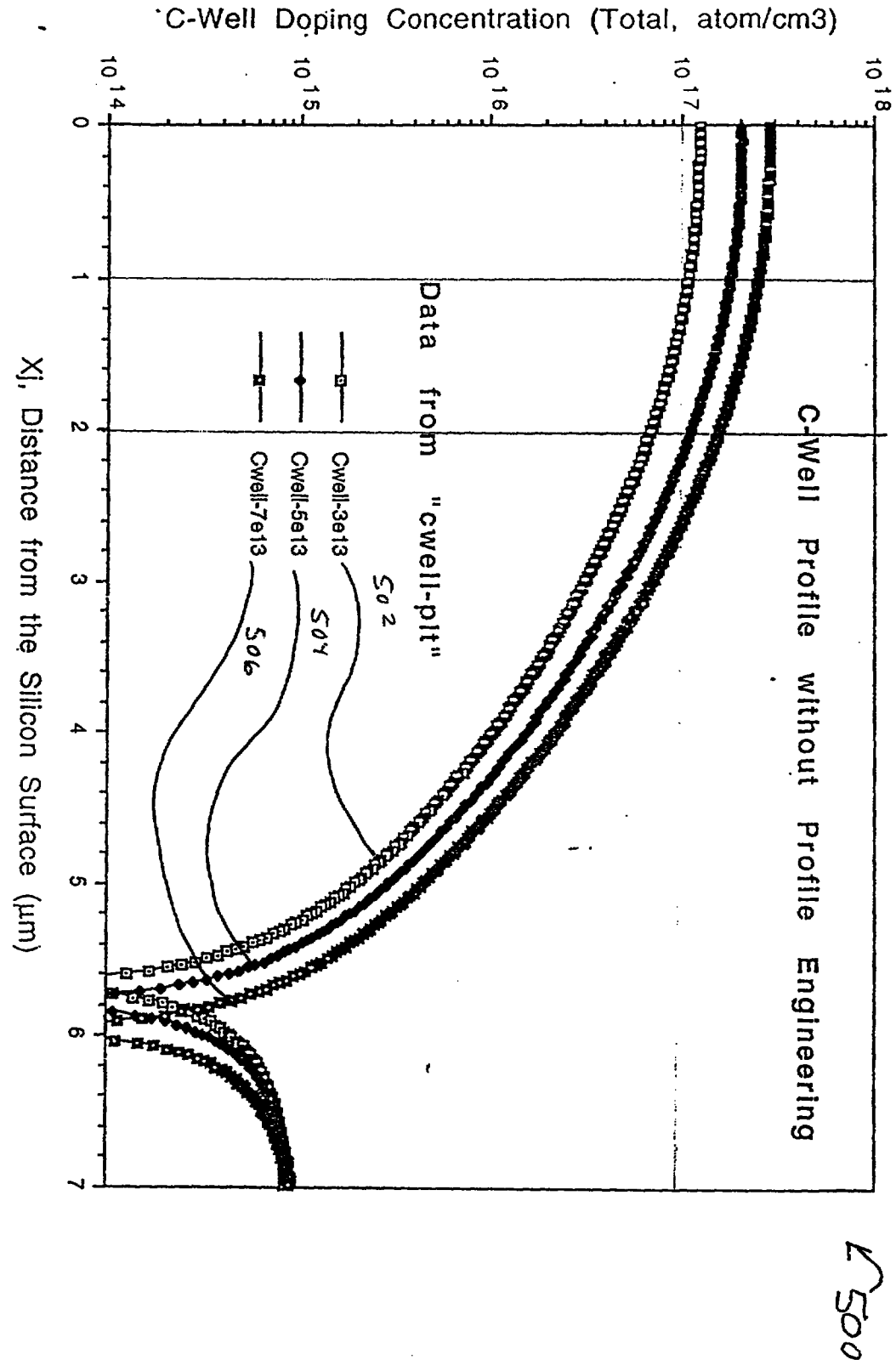


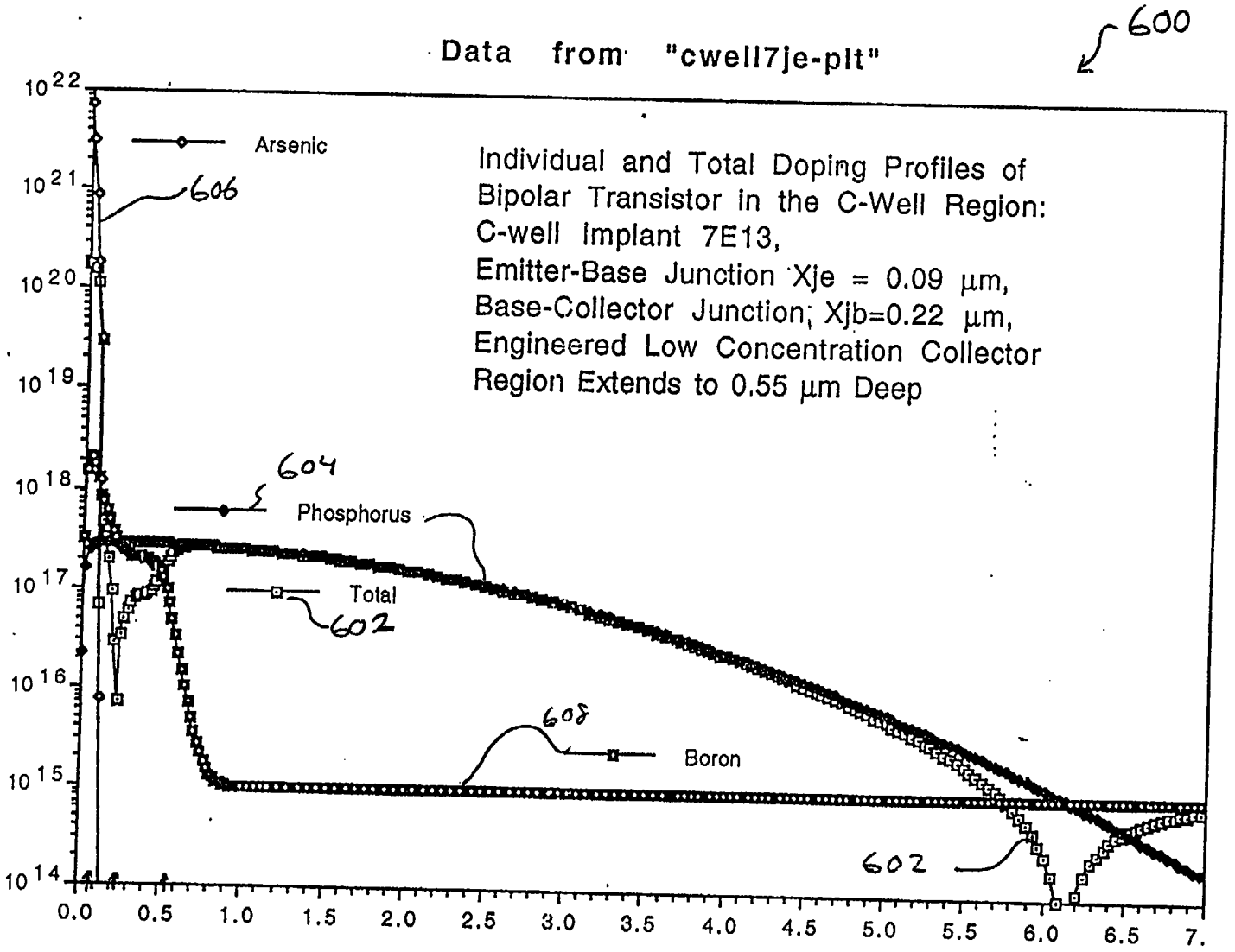
Fig. 5 (Prior Art)

500

This Sheet Has Been Replaced

THIS SHEET HAS BEEN REPLACED

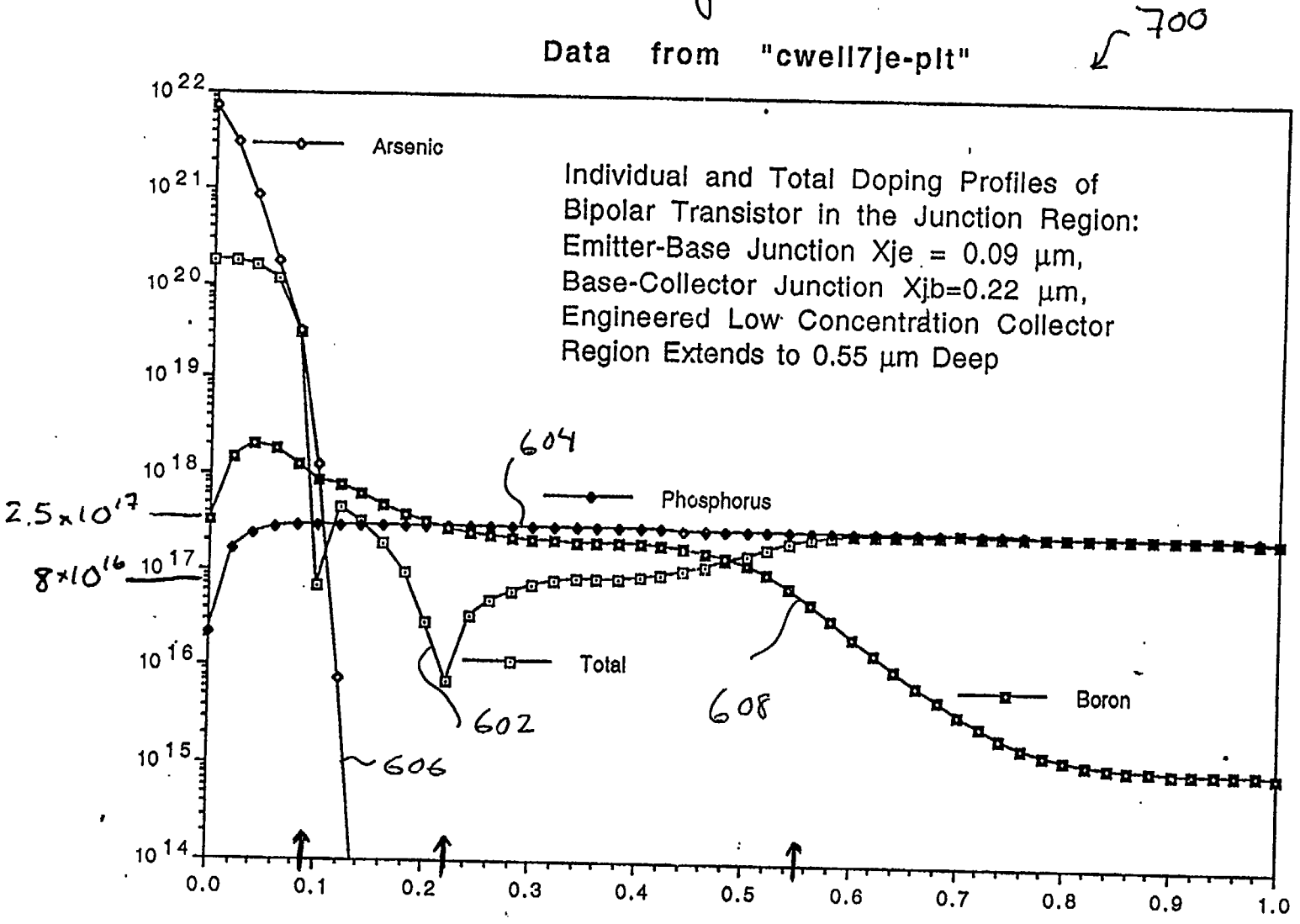
Fig. 6



THIS SHEET HAS BEEN REPLACED

This Sheet Has Been Replaced

Fig. 7



THIS SHEET HAS BEEN REPLACED

This Sheet Has Been Replaced

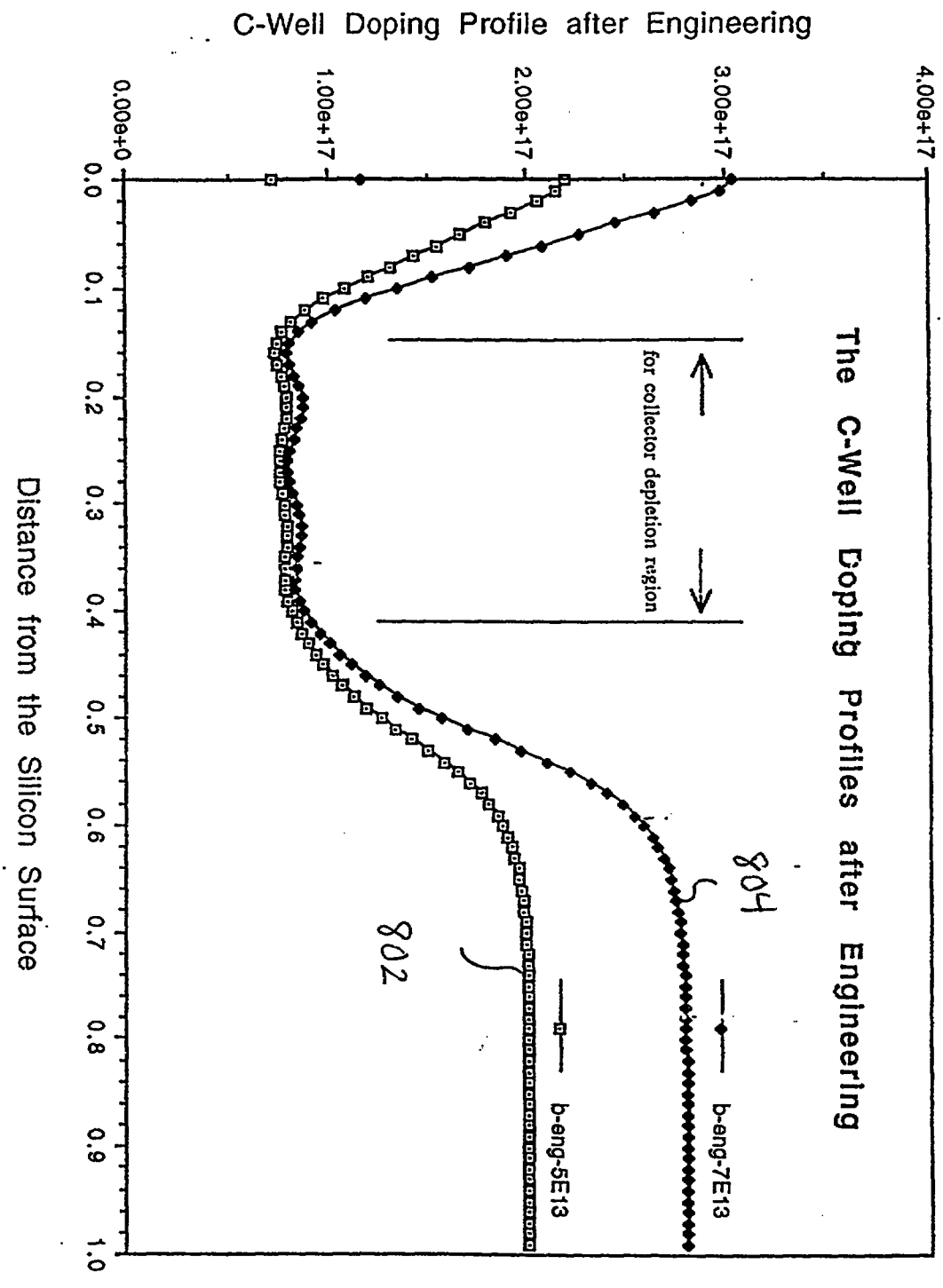


Fig. 8

800

This Sheet Has Been Replaced

THIS SHEET HAS BEEN REPLACED

HIGH SPEED, LOW COST BiCMOS PROCESS USING PROFILE ENGINEERING

10 MAR 1998

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to semiconductors and, more particularly, to an improved process for making complementary metal oxide semiconductor (CMOS) compatible bipolar CMOS (BiCMOS) devices.

Discussion of Related Art

A BiCMOS circuit includes both bipolar and complementary metal oxide semiconductor (CMOS) transistors in the same circuit. BiCMOS circuits enjoy advantages of both bipolar circuits and CMOS circuits. Bipolar circuits may drive high capacitive loads and thus provide large circuit fan outs and operate at high speed. CMOS circuits are relatively small in size and consume less power than other technologies. A typical BiCMOS device uses the bipolar circuits as a push-pull current booster and the CMOS circuits as logic circuits and to drive the base current of the bipolar circuits.

Fig. 1 is a schematic diagram of an example of a BiCMOS logic circuit 50 operating as an inverter. A totem pole-type output buffer 52 comprises a pull-up NPN bipolar transistor Q1 and a pull-down NPN bipolar transistor Q2. The base of transistor Q2 is coupled to an output terminal of a CMOS inverter 54 comprising a PMOS FET Q3 and an NMOS FET Q4. PMOS FET Q3 supplies a base current to bipolar transistor Q1 so that the logic circuit outputs a high voltage (data "1"). NMOS FET Q4 pulls a base charge from bipolar transistor Q1 so that the logic circuit outputs a low voltage (data "0"). The base of pull-down NPN bipolar transistor Q2 is connected to the source of NMOS FET Q5, which is turned on or off by the potential at the node of bipolar transistors Q1, Q2.

Many BiCMOS fabrication techniques are complicated and cannot be fabricated in standard CMOS foundries. This makes BiCMOS designs difficult to implement for integrated circuit designers that rely on standard CMOS foundries.

REPLACEMENT SHEET
10 MAR 1998

Fig. 2 is a cross-sectional view of a triple well polysilicon emitter BiCMOS device 200, which may be fabricated in a standard CMOS foundry. This device includes a p-type substrate 202 on which an NPN bipolar transistor 204 and CMOS device 206 are formed. The CMOS device comprises an NMOS device 208 and a PMOS device 210. The NPN transistor 204 includes a collector defined in an n-type c-well 212, a p-type base region 214, and an n+ emitter 216 formed by doped polysilicon. The NPN transistor 204 also includes an n+ n-plug collector ring 218 which contacts the collector 212 and reduces series resistance.

The NMOS device 208 is formed in a p-well 220 defined in the p-type substrate 202 and includes n+ drain and source regions 222A, 222B, and a gate oxide layer 224 on which a doped polysilicon p-type gate 226 is formed.

The PMOS device 210 is formed in an n-well 230 and includes p+ drain and source regions 232A, 232B, and a gate oxide layer 234 on which a doped polysilicon n-type gate 236 is formed. A number of field oxide regions 240 are defined on the surface as isolation areas between devices.

A prior art method for manufacturing this BiCMOS device 200 is illustrated with reference to Figs. 3A - 3H. Fig. 3A shows a p-type substrate 202. The substrate may be a conventional p-type wafer having a resistivity of about 6 to 9 Ω cm^{-2}. A 310 nm thick sacrificial oxide layer 302 is formed on the substrate to provide a protective layer for formation of the n-plug.

The sacrificial oxide layer 302 is etched from the areas where the n-plug ring collector 218 is to be formed. A second etch, removing 120 nm silicon for the c-well lithography alignment, is also performed. The photoresist layer is stripped and the wafer is cleaned. The wafer is exposed to an oxidation step to grow a 20 nm thick screen oxide for the following implant steps. The n-plug ring is formed by an implant of arsenic at an energy of 150 keV and a dose of 1 x 10^{15} cm^{-3}. The result of these steps is illustrated in Fig. 3B.

Next, all of the oxide is stripped off of the wafer. A 30 nm stress release oxide (SRO) layer 304 is grown and then a 150 nm nitride layer 306 is deposited on the SRO layer by using low pressure chemical vapor deposition (LPCVD). These two layers are masked and the SRO and nitride layers 304, 306 are etched to create windows for forming the c-well 212. (These layers are also etched to create a window for the n-well 230 in the

REPLACEMENT SHEET
10 MAR 1998

following step with the n-well mask.) When the windows are provided, the c-well implant is performed using a conventional implant of phosphorus at an energy of 150 keV with a maximum dose of 3 x 10^{13} cm^{-3}. After the c-well and n-well implant, an n-well/c-well oxidation step is carried out at 1050°C to grow an oxide layer 307 of 4000Å. The result of these steps is shown in Fig. 3D.

Conventional CMOS steps follow: the nitride layer over the p-well is etched off and the p-well implant is carried out as the 3800Å n-well/c-well oxide protects the n-well/c-well from the implant. The oxide layer 307 is then removed. A CMOS p-well drive-in step is carried out at 1150° for 8 hours.

As seen in Fig. 3E, a number of field oxide regions (FOX) 240 are formed on the substrate 202. These FOX regions 240 may be formed in any well-known manner.

A gate oxide 234 is grown on the substrate surface in a conventional manner. Then, the gate oxide is etched off over the base area 214 to form a base window with a base mask. The result of these steps is shown in Fig. 3F.

Next, a base implant is performed using a p-type impurity such as BF_2 at an energy of 80 keV and a typical dose of 2 x 10^{13} cm^{-3}. This forms the p-type base 214. The wafer is cleaned and approximately 20Å of oxide is removed using a precise oxide HF in 50:1 HF for 10 sec to remove oxide from the base area before polysilicon deposition. The result of these steps is shown in Fig. 3G.

Next, polysilicon deposition is performed. The NMOS and PMOS polysilicon gate structures 226, 236 are located on the gate oxide; a polysilicon emitter 217 is located on the substrate surface, in contact with the p-type base 214. The polysilicon emitter 217 is doped with an extremely high arsenic implant. The dose is as high as 1 x 10^{16} cm^{-3} at an energy of 50 keV, which is four times higher than a conventional CMOS polysilicon implant. This high dose eliminates the two dimensional effect for the narrow emitter and provides high emitter concentration for high emitter injection. A shallow emitter drive-in step is performed. This drive-in results in a very shallow n+ layer 216 in the base area 214.

The next step is the polysilicon patterning with over-etch to remove polysilicon stringers along steps as well as etching away the n+ layer 216 in the extrinsic base region formed during the emitter drive-in step. A normal CMOS over-etch process is used because of the gate oxide beneath the polysilicon to protect the source and drain regions. But in this case, the bipolar base part 214 is directly exposed to etching without oxide protection, so

REPLACEMENT SHEET
10 MAR 1998

that a certain amount of silicon in the extrinsic base area is etched away. The result of these steps is shown in Fig. 3H.

Conventional CMOS steps follow including n-LDD, p-LDD, spacer formation, NMOS source and drain implant, and PMOS source and drain implant.

As noted above, this BICMOS device may be fabricated in many CMOS foundries without substantially changing the CMOS components. The c-well has a uniform profile. That is, the c-well has a dopant concentration which is highest near the substrate surface and which decreases as it deepens from the surface. The c-well is doped in this manner to improve frequency-current response by lowering the c-well sheet resistance (R_{sc}). However, lowering R_{sc} degrades the BV_{ceo} i.e., collector-emitter breakdown voltage breakdown. Thus, in this device, the optimum R_{sc} which may be achieved is 300 Ω/sq and, as a tradeoff, a 4V BV_{ceo} and a maximum f_T (cut off frequency) of 15 GHz. This is because a lower R_{sc} results in a higher f_T.

It is an object of the present invention to provide a CMOS compatible BiCMOS fabrication technique which increases f_T and maintains an acceptable BV_{ceo}.

SUMMARY OF THE INVENTION

This and other objects of the present invention are provided by a BiCMOS device having a c-well fabricated using profile engineering (a multi-energy implant using accurate dosages and energies determined by simulation) to provide a higher c-well implant dose while creating a narrow region with relatively low concentration in the collector depletion range to avoid low base-collector breakdown. This achieves a much lower collector series resistance to pull-up a frequency response, a collector sheet resistance which can be as low as 150 Ω/sq., f_T may be increased to 20 GHz or higher, and epitaxial wafers are avoided. This latter advantage is desirable because epitaxial wafers are incompatible with CMOS processes performed by most foundries.

The c-well may be formed using profile engineering so that the carrier concentration near the base-collector junction in the collector region is made lower than the dopant concentration in the deep region of the c-well. For example, the base-collector junction may be formed with a depth of 0.25 μm and have a regional (engineered) c-well carrier concentration less than 10^{17} cm^{-3}; and the c-well may have a doping concentration higher than 10^{17} cm^{-3} at depths deeper than 0.6 μm.

REPLACEMENT SHEET
10 MAR 1998

Also, a method according to a preferred embodiment of the present invention eliminates a silicon etch step during the collector ring formation procedures to provide a more efficient method for creating a BiCMOS device than previously possible.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is described with reference to the following figures:

Fig. 1 is a schematic diagram of an example of a BiCMOS device logic circuit unit used as an inverter;

Fig. 2 is a cross sectional view of a prior art BiCMOS device;

Figs. 3A - 3H illustrate a conventional method for fabricating the BiCMOS device of Fig. 2;

Figs. 4A - 4H illustrate a method for fabricating a BiCMOS device according to the present invention;

Fig. 5 is a graph illustrating dopant concentration vs. distance from substrate surface in a prior-art c-well using three different dopant doses;

Fig. 6 is a graph illustrating dopant concentration vs. distance from substrate surface in a c-well according to the present invention;

Fig. 7 is a graph showing the concentrations of Fig. 6 for the depths between 0.0 and 1.0 μm from substrate surface; and

Fig. 8 is a linear scale of the graph of Fig. 7.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

To increase f_T while keeping BV_{ceo} at an acceptable level, the present invention provides a novel technology of precise profile engineering of the c-well. By using profile engineering in the c-well, a much higher c-well implant dose may be achieved, which provides a lower collector series resistance to pull up the frequency response. The profile engineering maintains a narrow region having a relatively low concentration in the collector depletion range which may be at a depth of, for example, from 0.2 μm to 0.5 μm, to avoid low base-collector breakdown. This allows the collector sheet resistance to be lowered down as low as 150 Ω/sq. The resultant BiCMOS structure looks similar to the structure shown in Fig. 2, with the most significant difference being that the c-well concentrations

REPLACEMENT SHEET
10 MAR 1998

are different, as described below. The present invention also eliminates a silicon etch step during the n-plug formation, and thus improves the morphology of the device.

A method for fabricating a BiCMOS device according to the present invention is described with reference to Figs. 4A - 4L. Fig. 4A shows a p-type substrate 202. The substrate is preferably a conventional p-type wafer having a resistivity of about 6 to 9 Ω/cm^2. A stress release oxide (SRO) 408 is grown on the substrate 202. Preferably, the SRO 408 is 30nm thick. Next, a nitride layer 410 is deposited on the SRO. Preferably, the nitride layer 410 is 150nm thick and deposited using LPCVD. Using photolithographic methods, photoresist is placed on the nitride layer 410 to define a c-well window 404. The nitride layer 410 is etched off, keeping the SRO 408 as a screen for a phosphorous implant described below. The photoresist is kept on. Next, a c-well implantation is performed using, for example, phosphorus at an energy of 150 keV and a dose of between 3-5 x 10^{13} cm^{-3}, to form a c-well 212'. The photoresist is removed and the wafer is cleaned. The result of these steps is seen in Fig. 4A.

As seen in Fig. 4B, using photolithographic methods, a second mask is used to define an n-plug (collector ring) 218. When the n-plug windows are opened, the exposed windows are doped with an n+ impurity such as arsenic, preferably at an energy of 150 keV and a dose of about $1x10^{15}$ cm^{-3}. This n-well doping step results in a reduced collector contact series resistance. The mask is then removed. After the n-plug implant, a c-well drive in step is carried out, preferably at 1150°C for 8 hours or 1175°C for 200 minutes. The result of these steps is seen in Fig. 4B.

As seen in Fig. 4C, using photolithographic techniques, a third mask is used to define an n-well 412 window. The nitride layer 410 is removed for the n-well implant and LOCOS steps. The nitride layer 410 is preferably removed using a plasma etch. The n-well is created, for example, using an n-type impurity such as phosphorous. Preferably, this is done at an energy of 150 keV and a dose of $8x10^{12}$ cm^{-3}. The result of these steps is seen in Fig. 4C.

Next, the n-well/c-well LOCOS oxidation is performed to form a sacrificial LOCOS oxidation layer 414. This layer preferably has a thickness of 380 nm. Next, the remainder of the nitride layer 410 is removed, preferably using H_3PO_4 at 170°C for 60 minutes. Next, the p-well implant is performed by implanting a p-type impurity, such as implanting boron at an energy of 50 keV and a dose of 4 x 10^{12} cm^{-3}. Next, a drive-in step is performed at

REPLACEMENT SHEET
18 MAR 1998

1150°C. This drive-in step finalizes the formation of the p-well 220 and the n-well 230. The result of these steps is seen in Fig. 4D.

Next, all the oxide is stripped to bare wafer in BOE and ready for the second nitride deposition. Note that after this step, the n-well and c-well areas 220, 212' are recessed about 160 nm below the p-well 220 plane. For simplicity, however, this is not shown in the figures. A second stress reduction oxide layer 416 is grown, preferably using dry oxidation at 900°C to create a 30 nm layer. A second nitride layer 418 is deposited using, for example, LPCVD to create a 150 nm layer. This second nitride layer 418 is etched to expose field oxide regions. The result of these steps is seen in Fig. 4E.

Next, a number of field oxide regions (FOX) 240 are formed on the substrate 202. These FOX regions may be formed in any well-known manner. The result of this step is seen in Fig. 4F.

Next a LOCOS field wet oxidation is performed. A nitride layer 418 is removed using, for example, H_3PO_4 at 170° for 60 minutes followed by an SRO HF dip off. The result of these steps is seen in Fig. 4F.

Next, optionally a V_t adjustment implant is performed to adjust the well doping to the desired V_t value. Next, a pre-gate oxide etch may be performed to clear active areas for gate oxidation.

Next, a gate oxide layer 430 is grown on the substrate surface in a conventional manner. Preferably, the gate oxide 430 has a thickness of 175Å + Δ, where Δ is an amount introduced to compensate for a HF dip thickness loss, discussed below. The gate oxide in the base active area is etched off over the c-well 212' area by lithography to form a window 432. This window is used to perform the collector profile engineering implants. The profile engineering uses one or more implants of a p-type dopant, such as boron, having predetermined dosages and energy levels precisely to control the total dopant concentration of the c-well 212'. Preferably, these implants are as follows:

REPLACEMENT SHEET
10 MAR 1998

Dopant	Energy	Dosage
Boron	65 keV	2.1 x 10^{12} cm^{-3}
Boron	120 keV	2.2 x 10^{12} cm^{-3}

These precisely engineered boron implants partially compensate the n-type phosphorous doping previously performed in the specified region.

The gate oxide over the base active area is etched away. The base is then doped to a p-type conductivity using, for example, boron at an energy of 20 keV and a dose of 2 x 10^{13} and 7°. This type of implant reduces channelling of implanted ions. This forms p-type base 214. The result of these steps is seen in Fig. 4G.

Next, an HF dip is performed to remove native oxide formed in base areas during photoresist stripping. This HF dip results in a small oxide loss Δ in the gate oxide 430. This thickness loss is Δ described above, which should be well controlled.

Next, polysilicon deposition is performed. The NMOS and PMOS polysilicon gate structures 226, 236 are located on the gate oxide (224, 234, respectively); a polysilicon emitter 216 is located on the substrate surface, in contact with the p+ base 214. Preferably, the polysilicon layer is 280 nm. The polysilicon emitter 216 is doped with an extremely high arsenic implant. The dose is as high as 2 x 10^{16} cm^{-3} at an energy of 50 keV. The implant is annealed and a shallow emitter drive-in step is performed. This drive-in also results in a thin n+ layer 216A in the extrinsic base area which will be etched away by a precise over-etch of the polysilicon. The result of these steps is seen in Fig. 4H. The same steps may also form a top capacitor plate for the PMOS device capacitor.

Conventional CMOS steps follow to complete the fabrication of the inventive BiCMOS device. These conventional steps include n-LDD, p-LDD, spacer formation, NMOS source and drain implants, and PMOS source and drain implants. These steps are well known to those skilled in the art and are not further described.

Fig. 5 is a graph 500 of a simulated profile of three c-well implants without using profile engineering, such as in the prior art device described below. The dosages are 3 x 10^{13} (line 502), 5 x 10^{13} (line 504), and 7 x 10^{13} (line 506), respectively. (Note that these last two dosages cannot be applied without proper profile engineering, but for purposes of

REPLACEMENT SHEET
10 MAR 1998

this simulation, it is assumed that they can be.) Note that in all three incidences, between 0 and 1 μm from the substrate surface, the doping concentration is between 1 x 10^{17} and 5 x 10^{17}. Thus, a very high dopant concentration in the c-well 212 occurs near the substrate surface.

Figs. 6 and 7 illustrate the advantage of profile engineering in the present invention. Fig. 6 is a graph 600 illustrating the simulated c-well profile of a c-well 212' using profile engineering according to the present invention. Fig. 7 is a graph 700 showing the same concentration for depths between 0 and 1 μm from the substrate surface. These graphs show the concentration of arsenic 606 (from the emitter 216A), phosphorus 604 (from the c-well 212'), boron 608 (the base), and total effective dopant concentration 602 as a function of the distance from a surface of the substrate. Note that the emitter-base junction X_{JB}, preferably occurs at 0.09 μm from the substrate surface and has a concentration of about $2x10^{20}$ cm-3. The base-collector junction X_{JB}, preferably occurs at approximately 0.22 μm collector total and has a concentration less than 10^{17} cm^{-3} near the base-emitter junction. The engineered low concentration collector region preferably extends from 0.22 μm to approximately 0.55 μm. This region is important to collector-emitter breakdown after profile engineering. The total average concentration is about $8x10^{16}$, which is much lower than the original level of $2.5x10^{17}$. This lower concentration region allows for a much thicker depletion layer for higher breakdown. On the other hand, this low concentration region is very limited around the base-collector junction and has a thickness of only about 5% of the collector well. The high concentration of the collector well can increase f_T. At depths below 0.6 μm, the effective total dopant concentration may be as high as 2.5 x 10^{17} cm^{-3}. It is this precise profile engineering which permits a high total concentration in the c-well, yet a low concentration near the substrate surface.

Fig. 8 is a graph 800 showing the data of Fig. 7 plotted on a linear scale for a dosage of 7 x 10^{13} (line 804) and a dosage of 5 x 10^{13} (line 802). Note the low total concentration in the collector depletion region from approximately 0.1 μm to 0.4 μm from the substrate surface.

Using profile engineering in the manner described above permits the c-well to be formed so that the dopant concentration in the emitter-base junction, base-collector junction, and collector region which is lower than a dopant concentration in other regions of the c-well. The base-collector junction may be formed at about 0.25 μm and have a dopant

REPLACEMENT SHEET
19 MAR 1990

concentration less than 10^{17} cm^{-3}; and the c-well may have a dopant concentration greater than 2.5 x 10^{17} cm^{-3} at depths deeper than 0.6 μm.

Disclosed is a BiCMOS device which provides a low collector series resistance without compromising the base-collector breakdown. This is achieved by using profile engineering to create a low carrier concentration at the base-collector junction, and collector region; yet providing a c-well having a very high overall concentration, thus lower R_{SC}. This achieves a much lower collector series resistance to pull-up a frequency response, a collector sheet resistance which can be as low as 150 Ω/sq., and f_T may be increased to 20 GHz or higher.

The above described embodiments of the invention are intended to be illustrative only. Numerous alternative embodiments may be devised by those skilled in the art without departing from the spirit and scope of the following claims.

* C L M S *

REPLACEMENT SHEET
10 MAR 1998

We claim:

1. A method for fabricating a bipolar complementary metal oxide semiconductor (BiCMOS), the method comprising the steps of:

   a. forming in a substrate having a first conductivity type a complementary metal oxide semiconductor device, comprising an n-type metal oxide semiconductor device formed in a p-type well and a p-type metal oxide semiconductor device formed in a n-type well;

   b. forming a bipolar transistor having a base, an emitter, and a collector, the transistor being formed in a c-well having a second conductivity type opposite the first conductivity type; and

   c. forming the c-well using profile engineering so that a dopant concentration in a base-collector junction and a collector region is lower than a dopant concentration in other regions of the c-well.

2. The method of claim 1, wherein the step of forming the c-well further includes the steps of:

   a. forming the base-emitter junction having a highly doped n+ polysilicon emitter, having a dopant concentration about 2×10^{20} cm^{-3};

   b. forming the base-collector junction at about 0.25 μm and having a collector total concentration less than 10^{17} cm^{-3} near the base-emitter junction; and

   c. the c-well having a dopant concentration greater than 10^{17} cm^{-3} at depths greater than 0.6 μm.

3. The method of claim 1, wherein the step of forming the c-well further includes the steps of:

   a. forming in the substrate a c-well area by implanting first impurities having the second conductivity type;

   b. forming in the substrate a collector ring by implanting second impurities having the second conductivity type; and

   c. performing profile engineering on the c-well by implanting third impurities having the first conductivity type using predetermined dosages and energy levels.

* C L M S *

REPLACEMENT SHEET
10 MAR 1998

4. The method of claim 3, further comprising selecting the first impurities to be phosphorous atoms, selecting the second impurities to be arsenic atoms, and selecting the third impurities to be boron atoms.

5. A method for fabricating a bipolar complementary metal oxide semiconductor on a substrate having a first conductivity type, the method comprising the steps of:

a. growing an oxide layer on a surface of the substrate;

b. depositing on the oxide layer a nitride layer;

c. removing first selected portions of the nitride layer to expose a collector well window;

d. doping the collector well window with first impurities to a second conductivity type to form a collector well;

e. exposing a second selected portion of the substrate within the collector well to expose an n-plug collector ring window;

f. doping with a high concentration of second impurities to the second conductivity the second selected portions to form an n-plug collector ring;

g. forming complementary oxide semiconductor devices on the substrate;

h. growing a gate oxide on active areas of the substrate surface;

i. exposing a third selected portion of the gate oxide to expose the collector well;

j. using profile engineering, doping the collector well with third impurities of the first conductivity type at predetermined energy levels and dosages;

k. forming above the collector well a base region having the first conductivity type; and

l. depositing polysilicon above the base region and doping the polysilicon to the second conductivity type to form an emitter.

REPLACEMENT SHEET
19 MAR 1998

ABSTRACT

HIGH SPEED, LOW COST BiCMOS PROCESS USING PROFILE ENGINEERING

A bipolar complementary metal oxide semiconductor device has a c-well fabricated using profile engineering (a multi-energy implant using accurate dosages and energies determined by advance simulation) to provide a higher c-well implant dose while creating a narrow region with relatively low concentration in the collector depletion range to avoid low base-collector breakdown. This achieves a much lower collector series resistance to pull-up a frequency response, a collector sheet resistance which can be as low as 150 Ω/sq., and f_T may be increased to 20 GHz or higher.

FIG. 1

REPLACEMENT SHEET
10 MAR 1998

FIG. 1
(PRIOR ART)

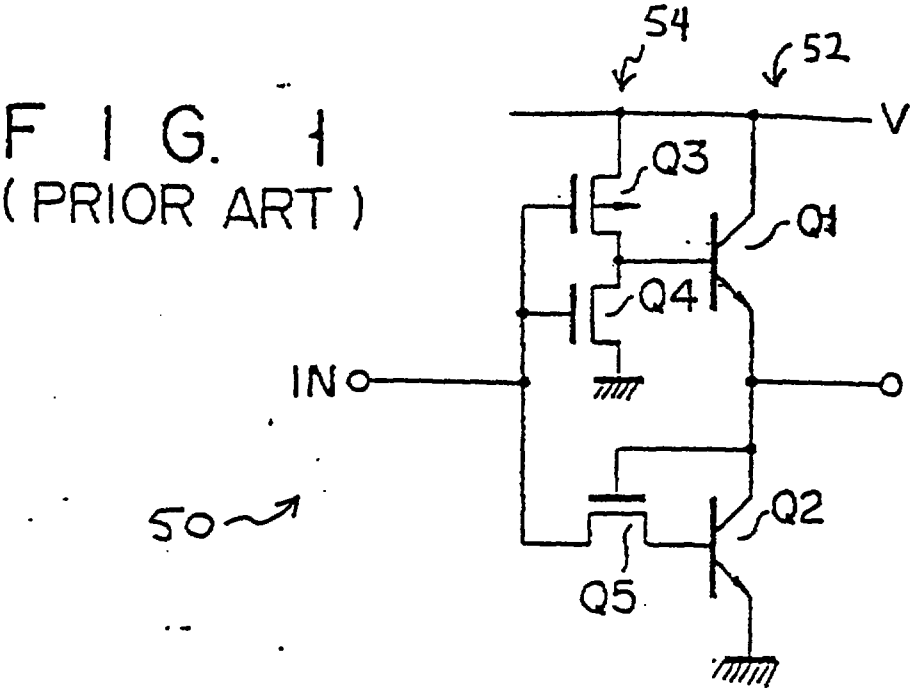
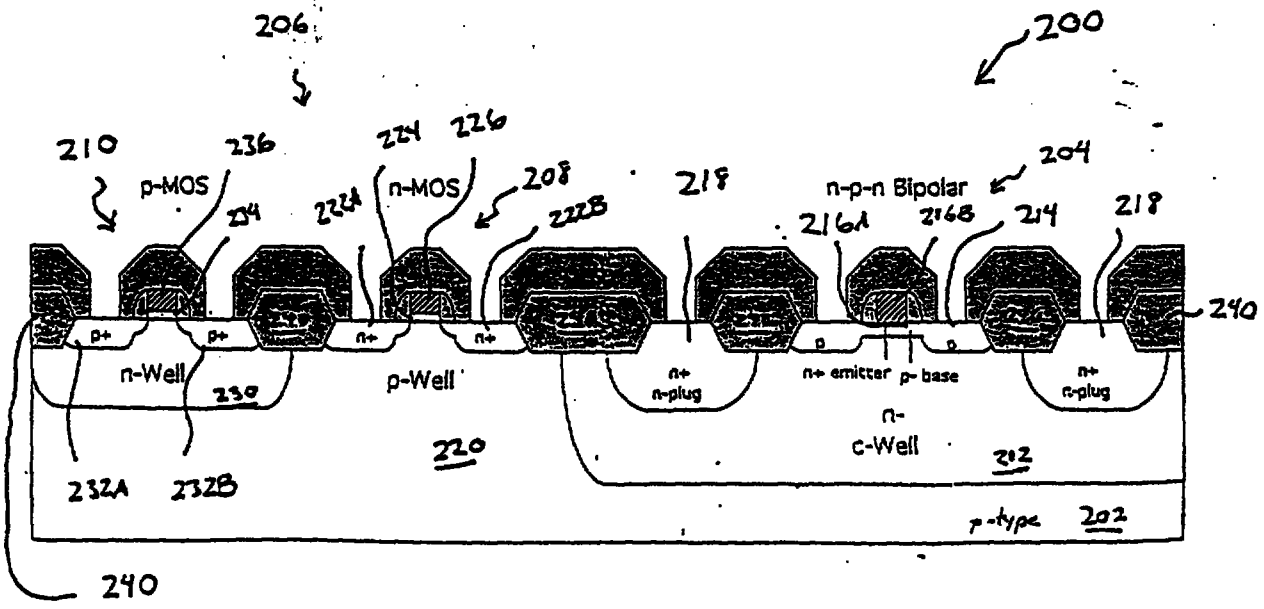


Fig. 2
(Prior Art)



REPLACEMENT SHEET
19 MAR 1998

Fig. 3A
(Prior Art)

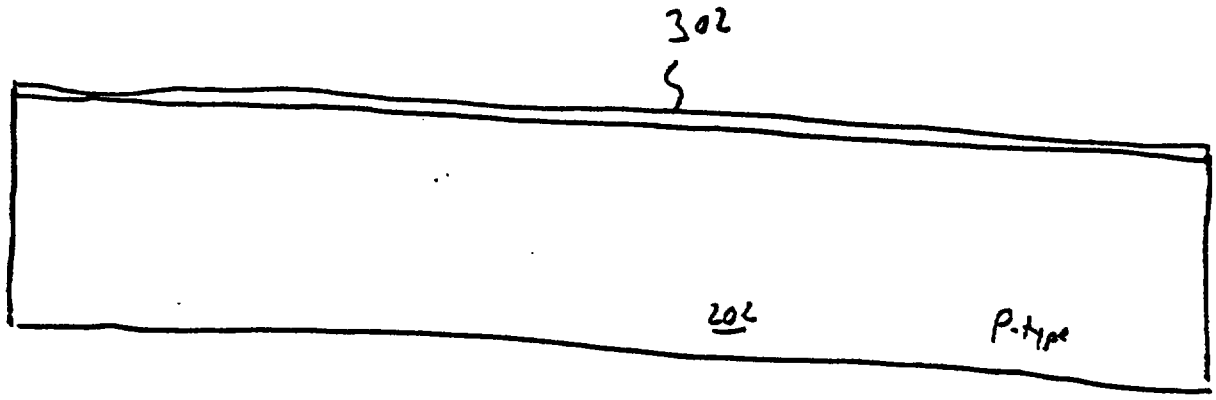
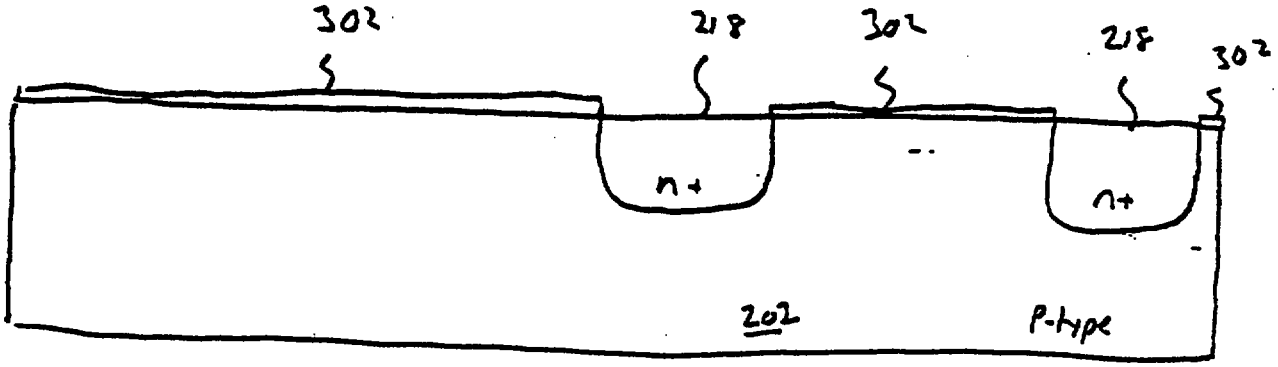


Fig. 3B
(Prior Art)



REPLACEMENT SHEET
19 MAR 1998

Fig. 3C
(Prior Art)

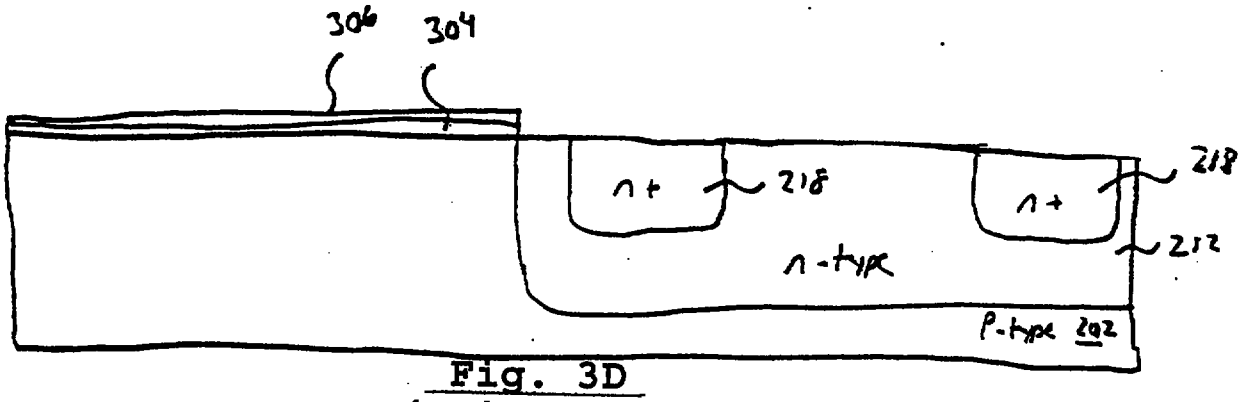


Fig. 3D
(Prior Art)

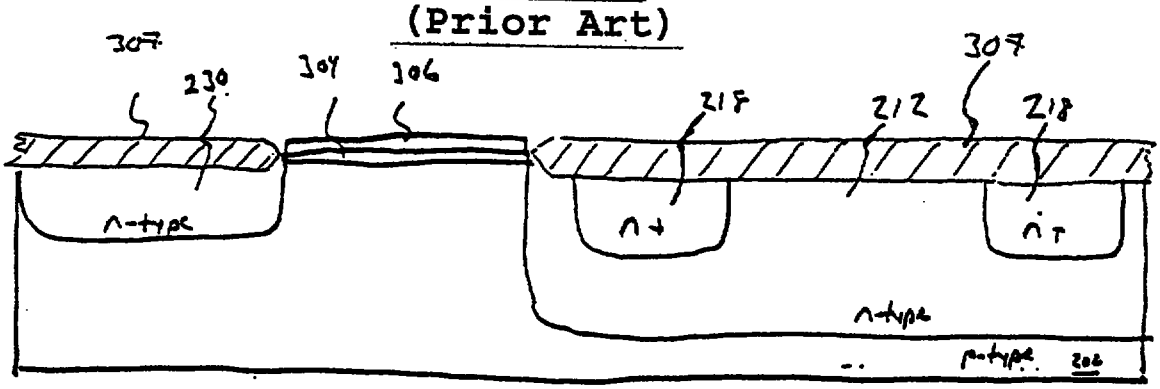
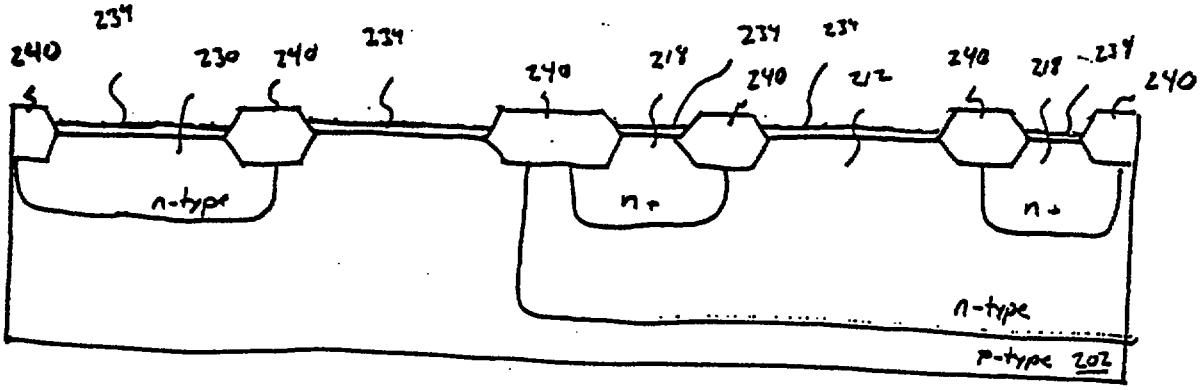


Fig. 3E
(Prior Art)



REPLACEMENT SHEET
10 MAR 1998

Fig. 3F
(Prior Art)

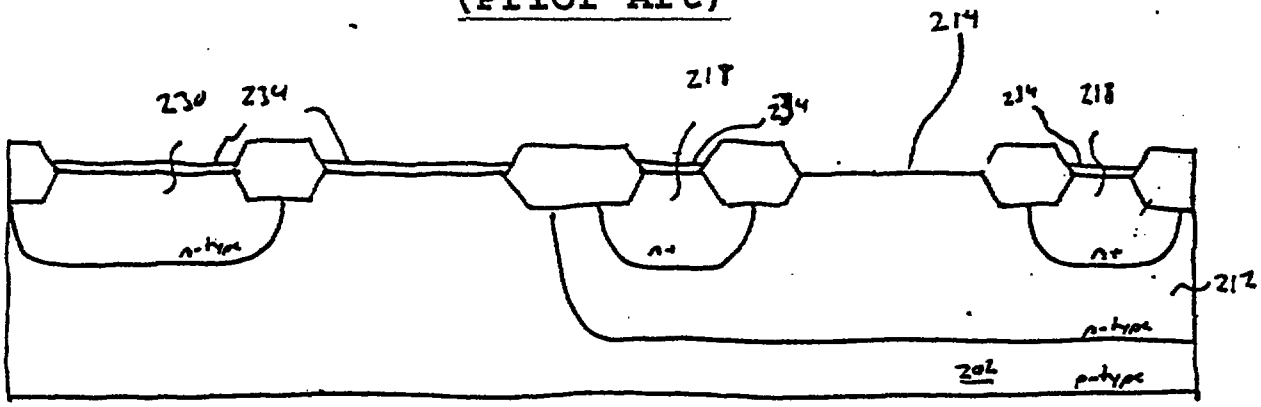


Fig. 3G
(Prior Art)

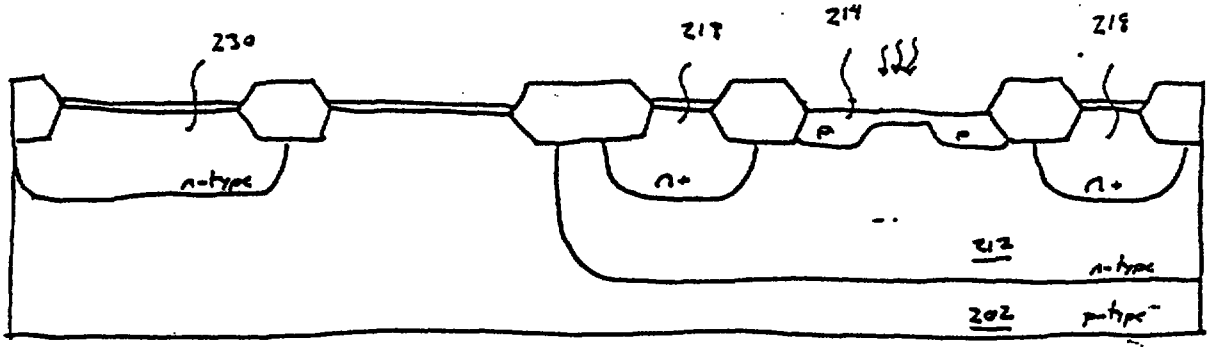
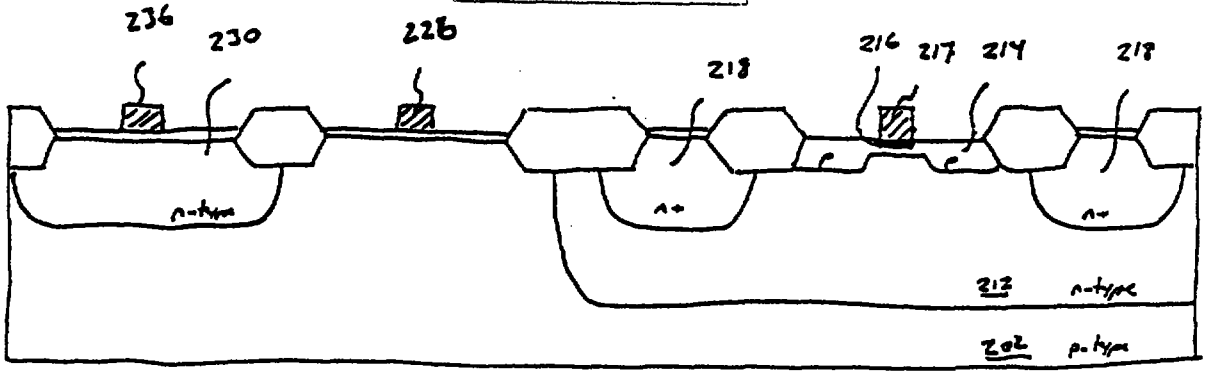


Fig. 3H
(Prior Art)



REPLACEMENT SHEET
18 MAR 1998

Fig. 4A

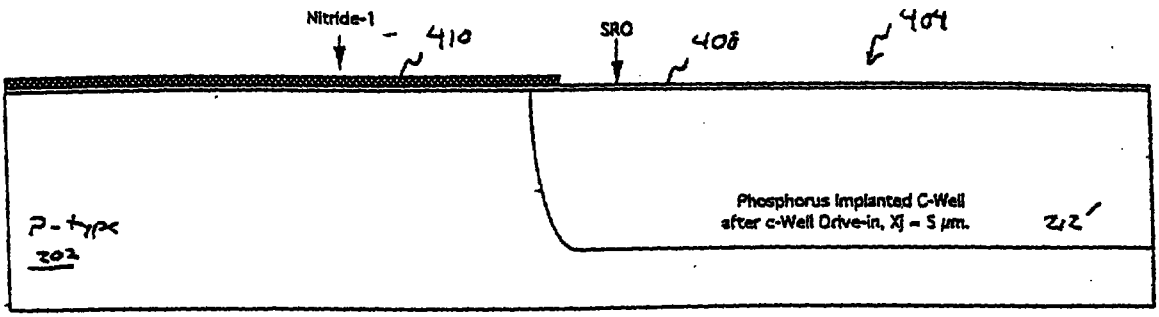


Fig. 4B

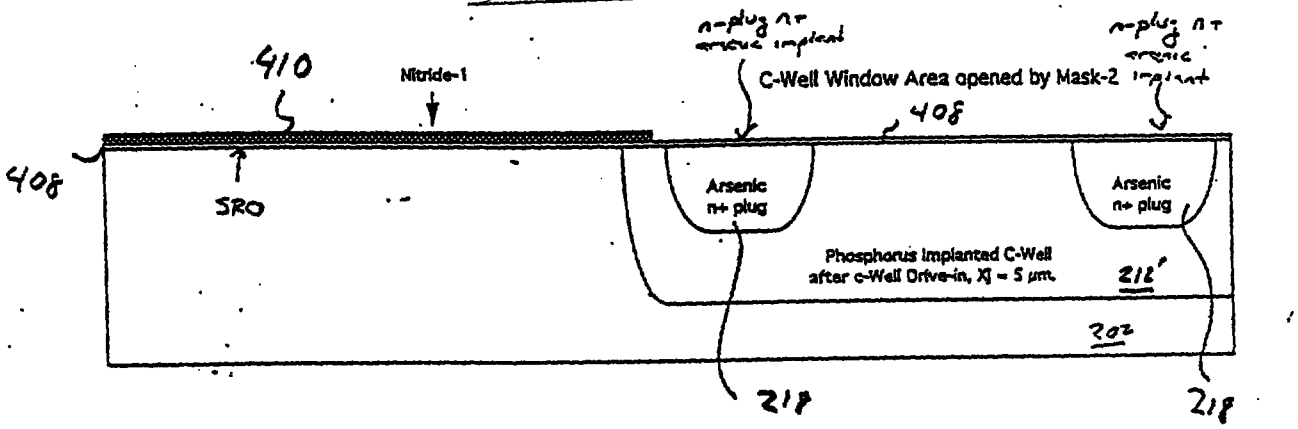
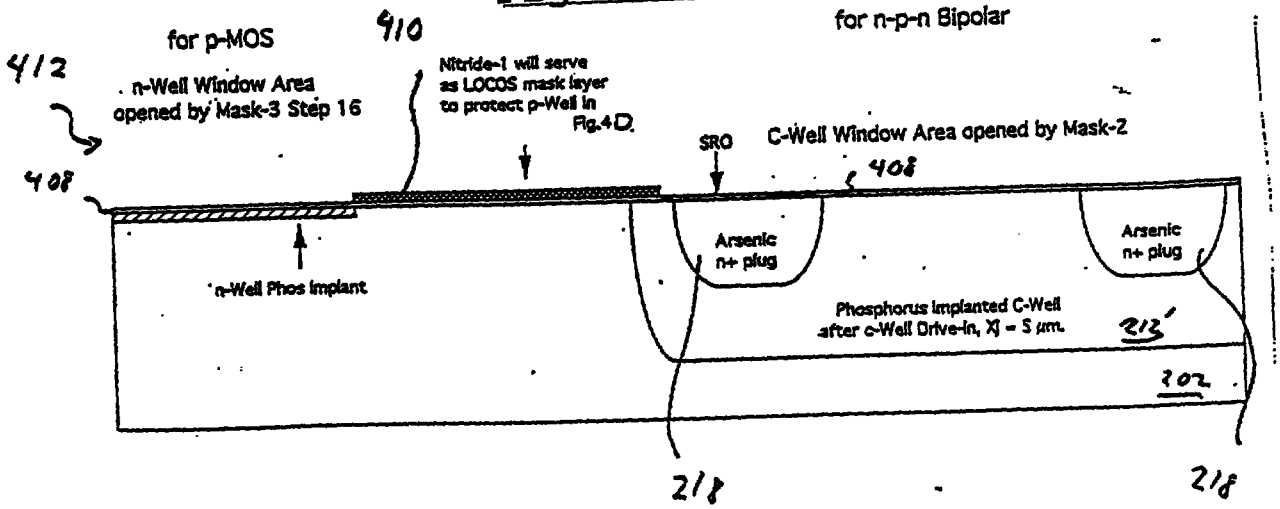


Fig. 4C



REPLACEMENT SHEET
1 8 MAR 1998

Fig. 4D

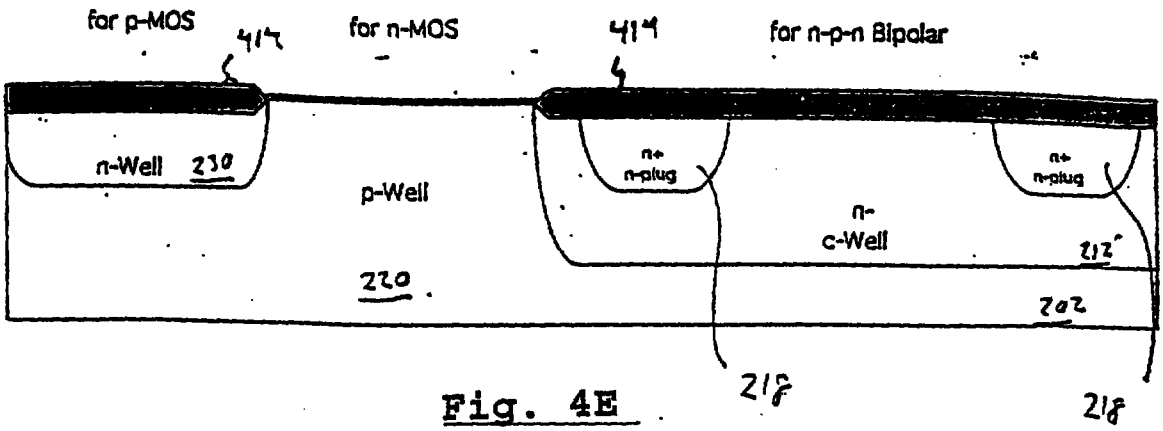


Fig. 4E

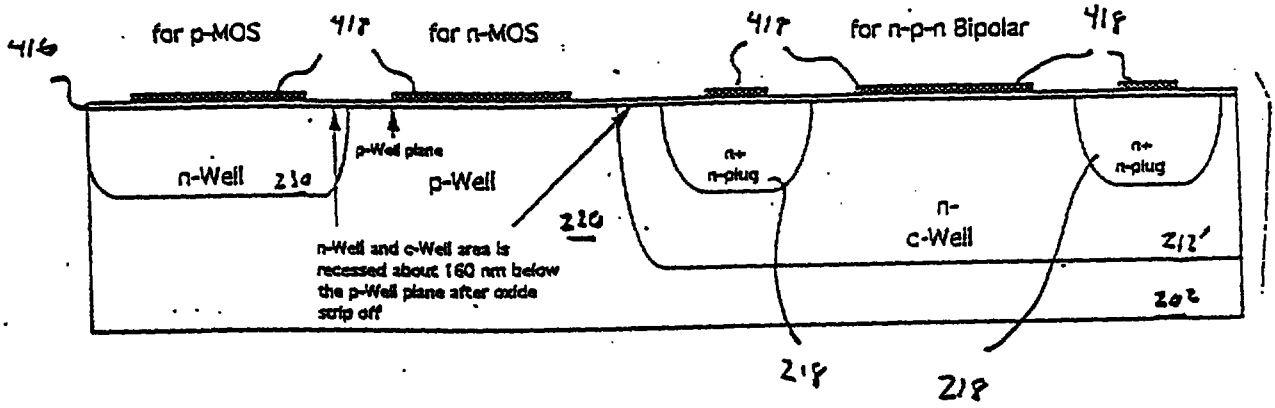
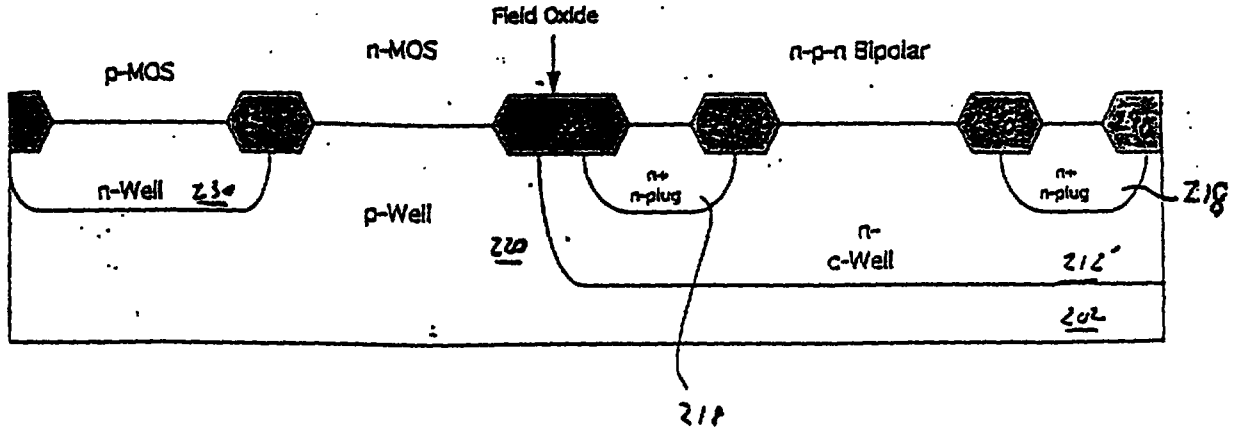


Fig. 4F



REPLACEMENT SHEET
10 MAR 1999

Fig. 4G

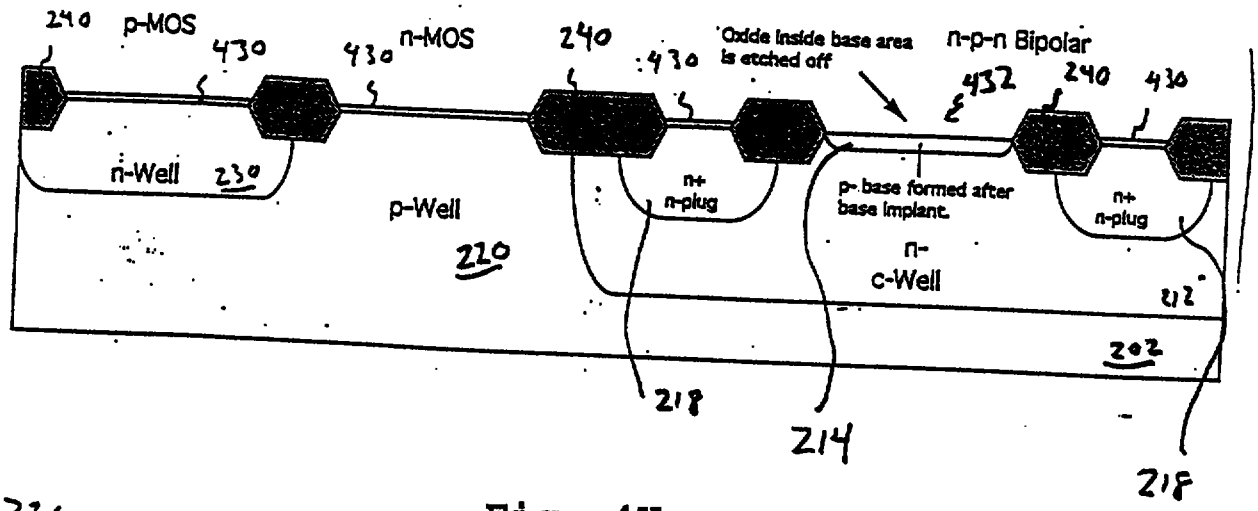
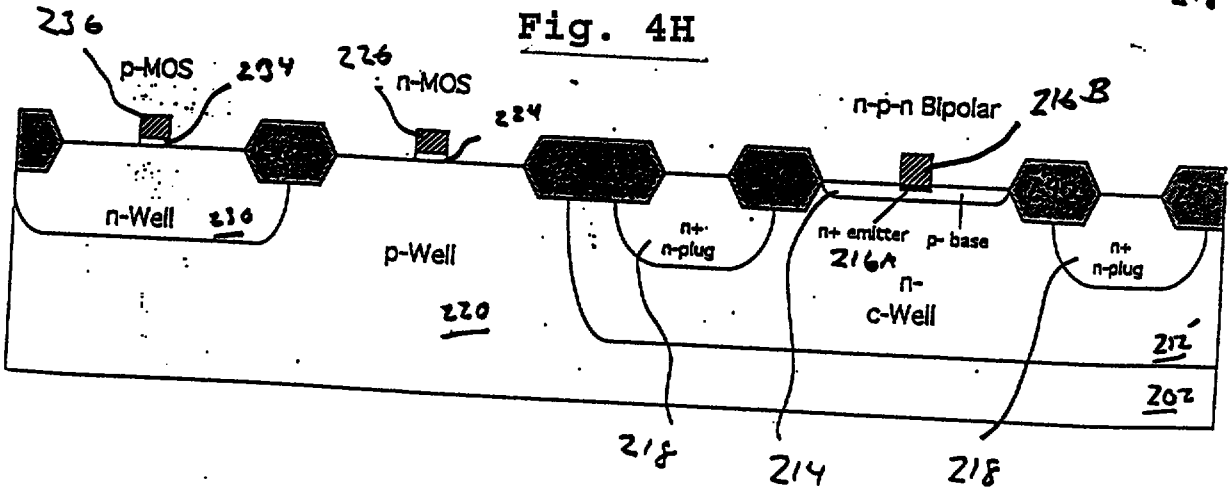


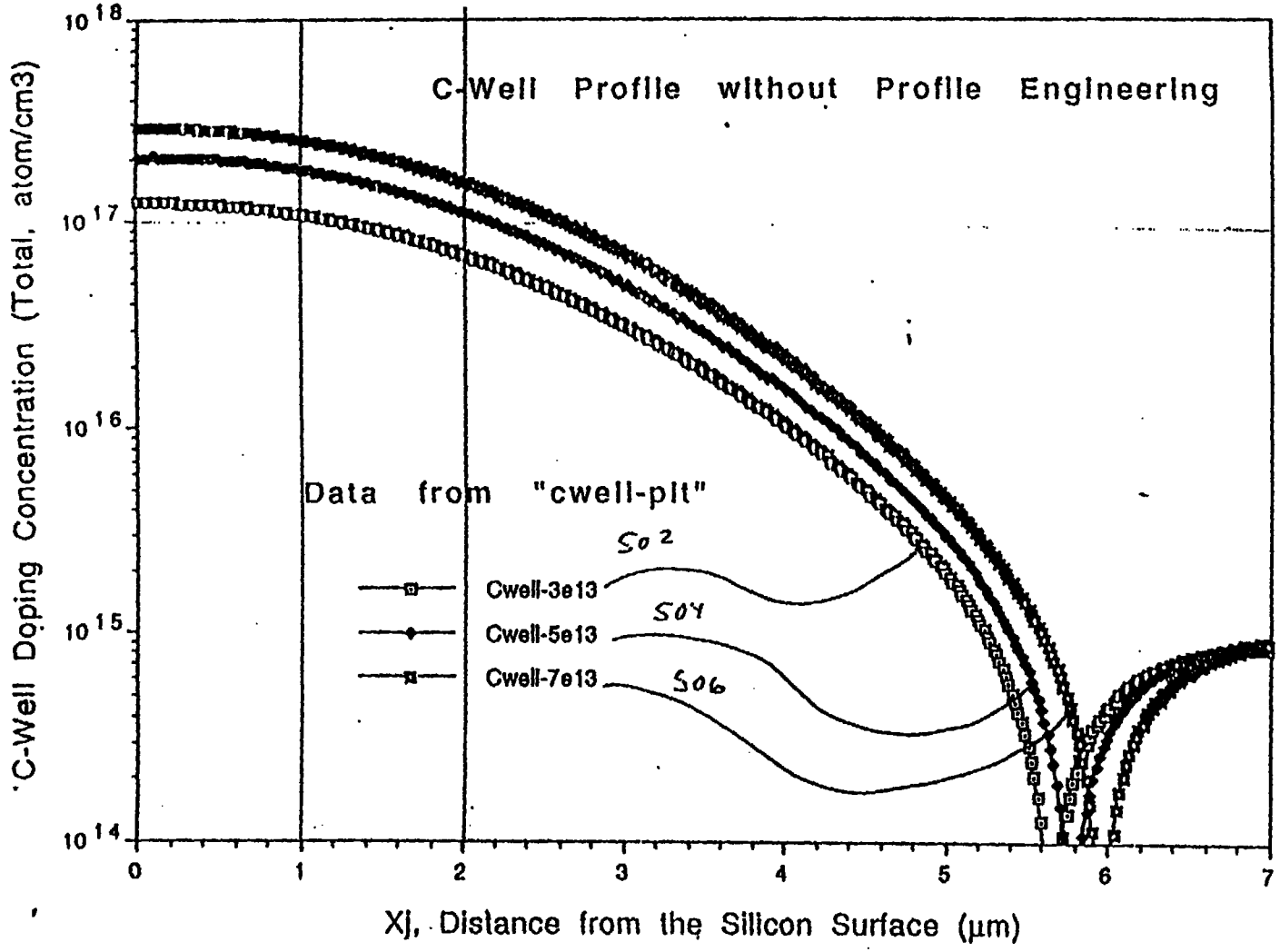
Fig. 4H



REPLACEMENT SHEET
19 MAR 1998

8/

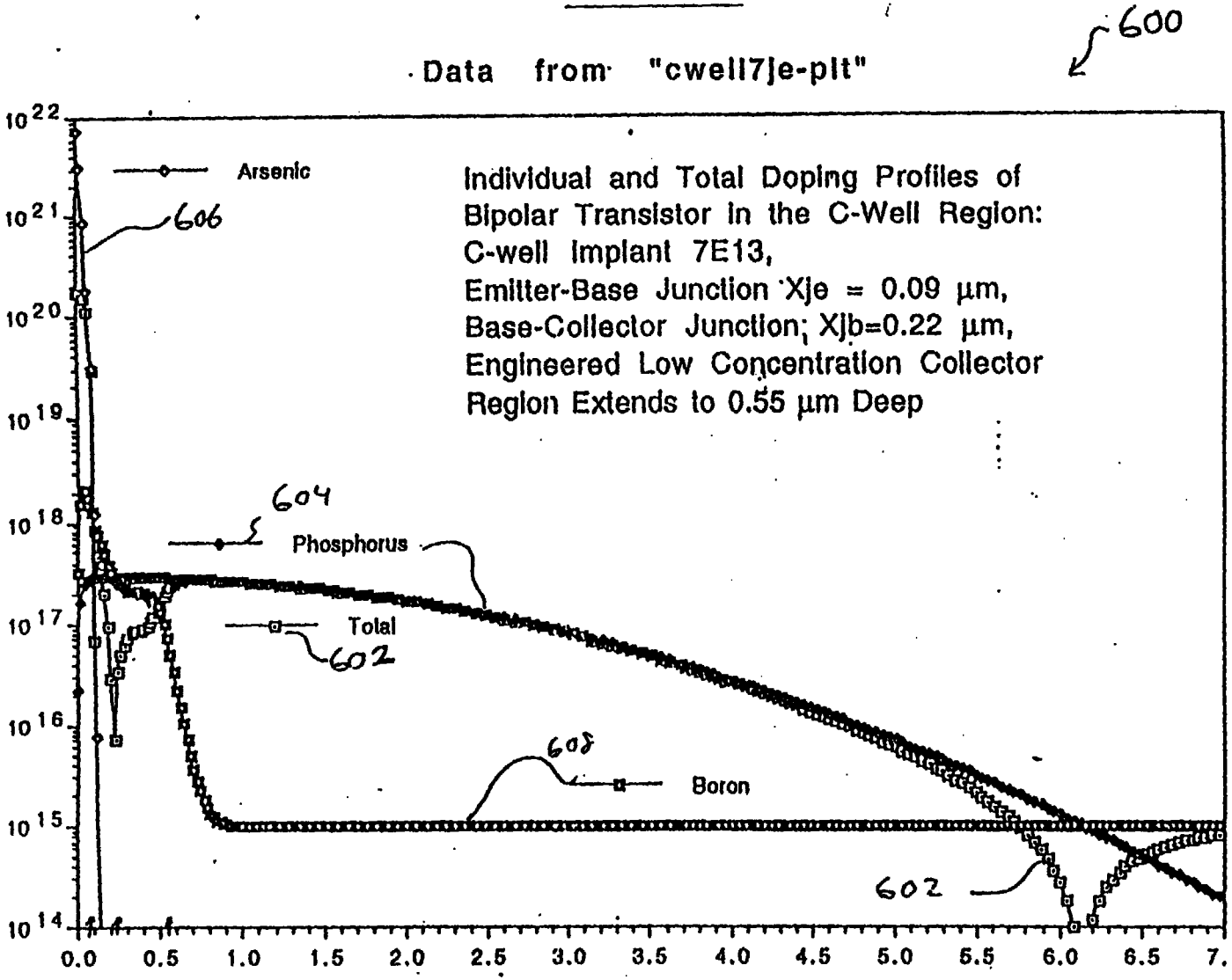
Fig. 5 (Prior Art)



500

REPLACEMENT SHEET
10 MAR 1998

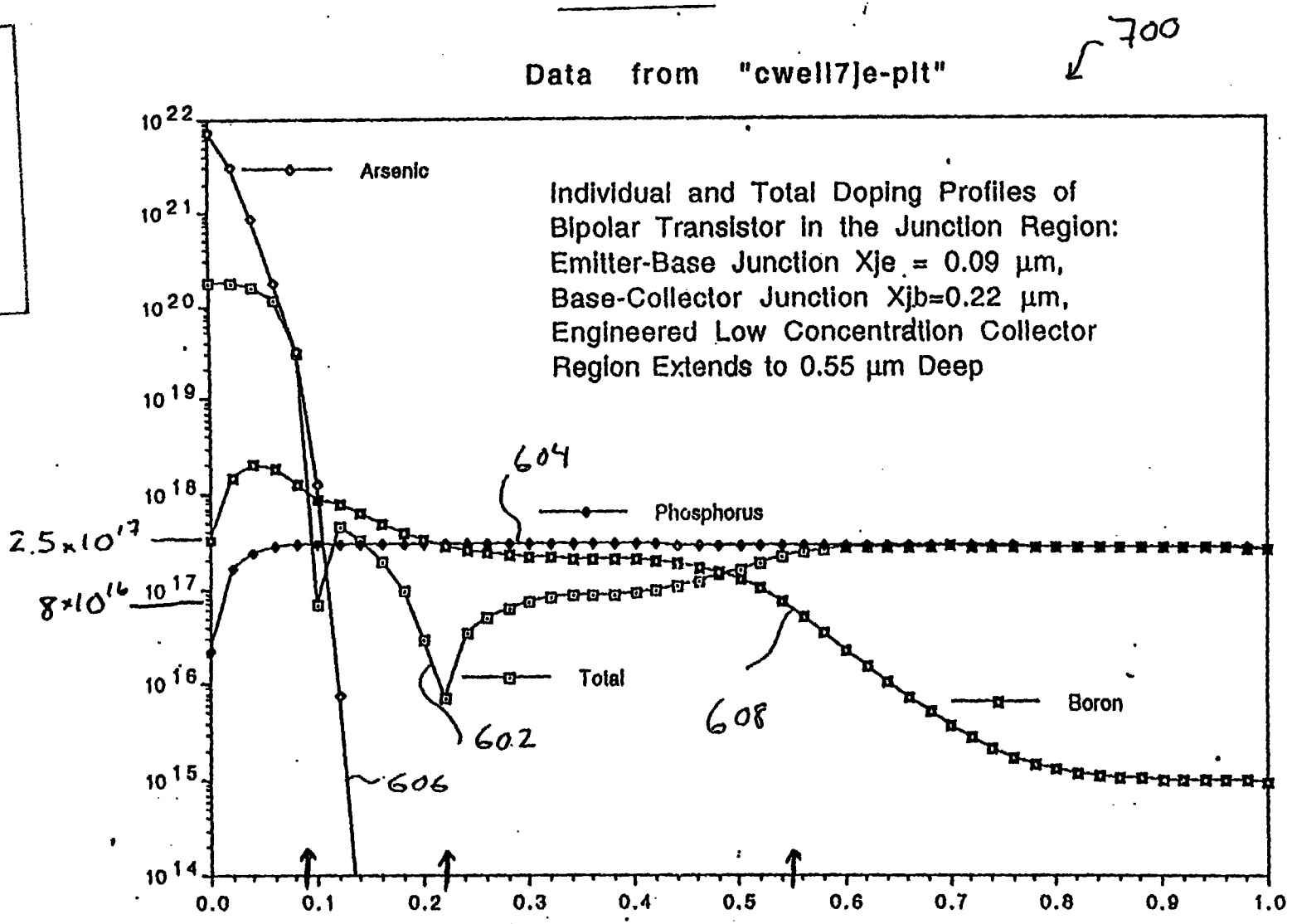
Fig. 6



9

REPLACEMENT SHEET
19 MAR 1998

Fig. 7



10

REPLACEMENT SHEET
10 MAR 1998

Fig. 8

