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(54) **NANOWIRES**

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H01L 29/06 (2006.01)

(52) **U.S. Cl.** **257/9**; 257/500; 428/401

(58) **Field of Classification Search** 257/9, 500; 428/401

See application file for complete search history.

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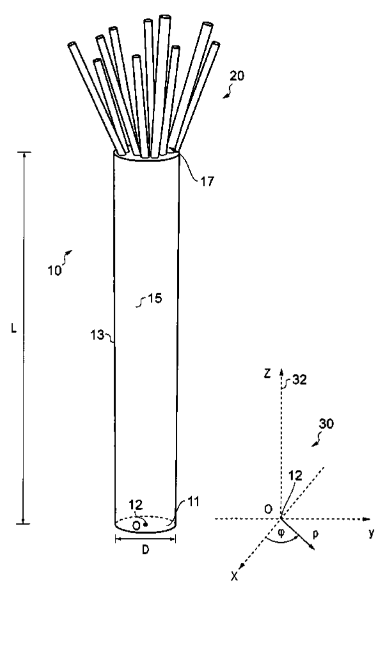
(57) **ABSTRACT**

An apparatus and a method of manufacturing the apparatus. The apparatus includes a main nanowire and branch nanowires emanating from the main nanowire. The main nanowire may have a first portion and a second portion. The first portion may have a first carrier concentration and the second portion may have a second carrier concentration, different to the first carrier concentration. Each branch nanowire may emanate from the first portion of the main nanowire. Each branch nanowire may emanate from the main nanowire at a substantially fixed distance along a length of the main nanowire.

10 Claims, 5 Drawing Sheets



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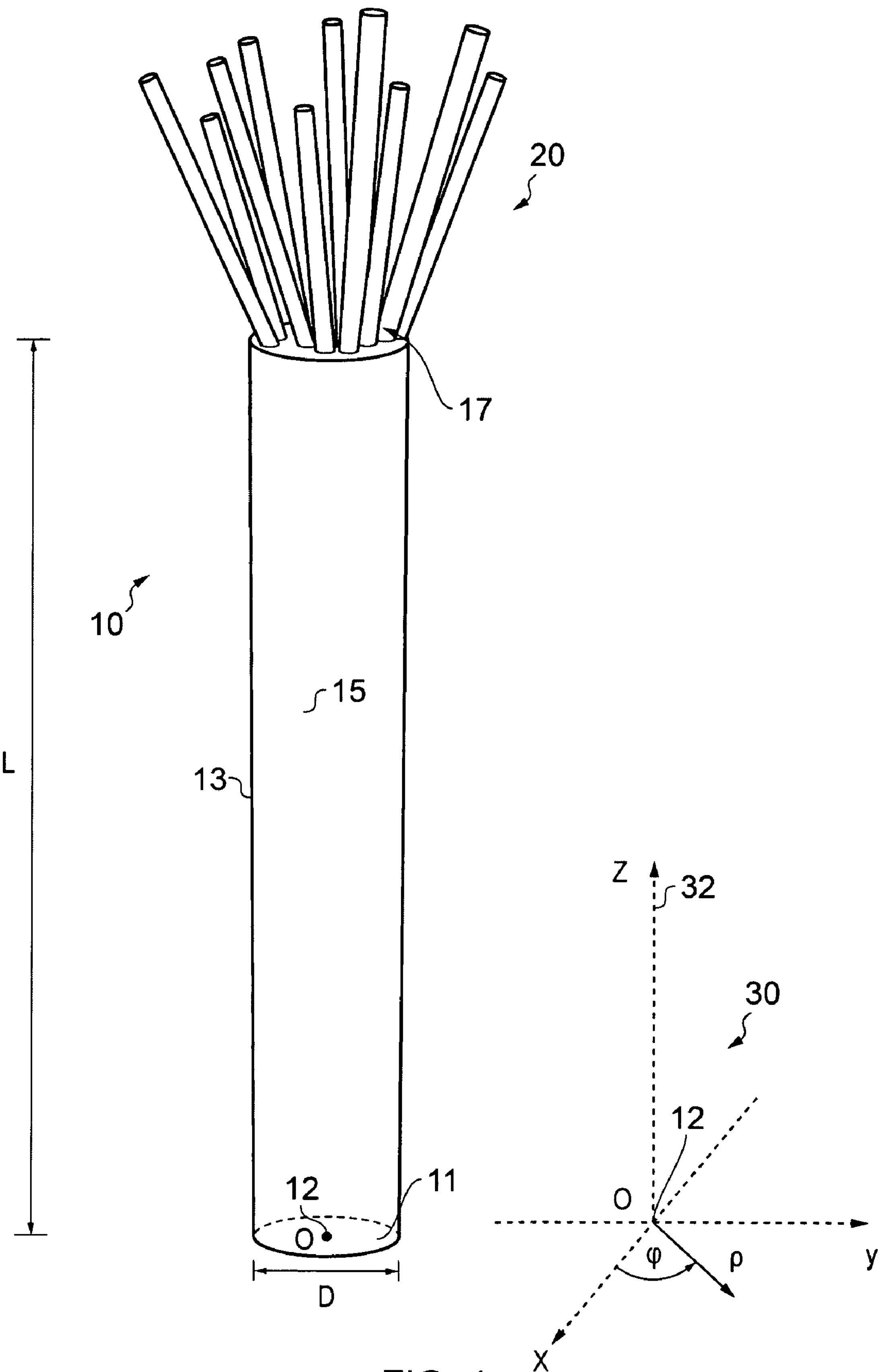


FIG. 1

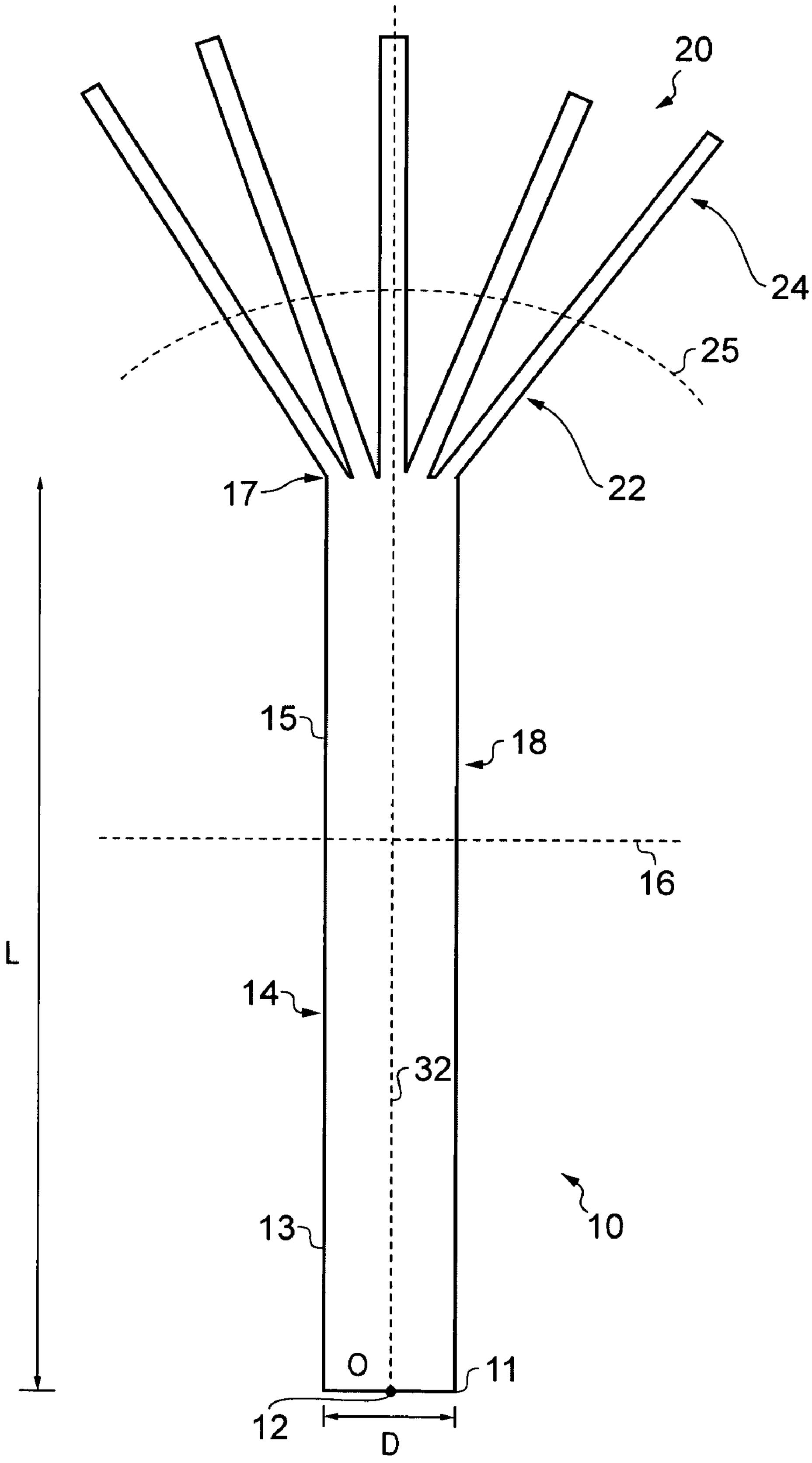


FIG. 2

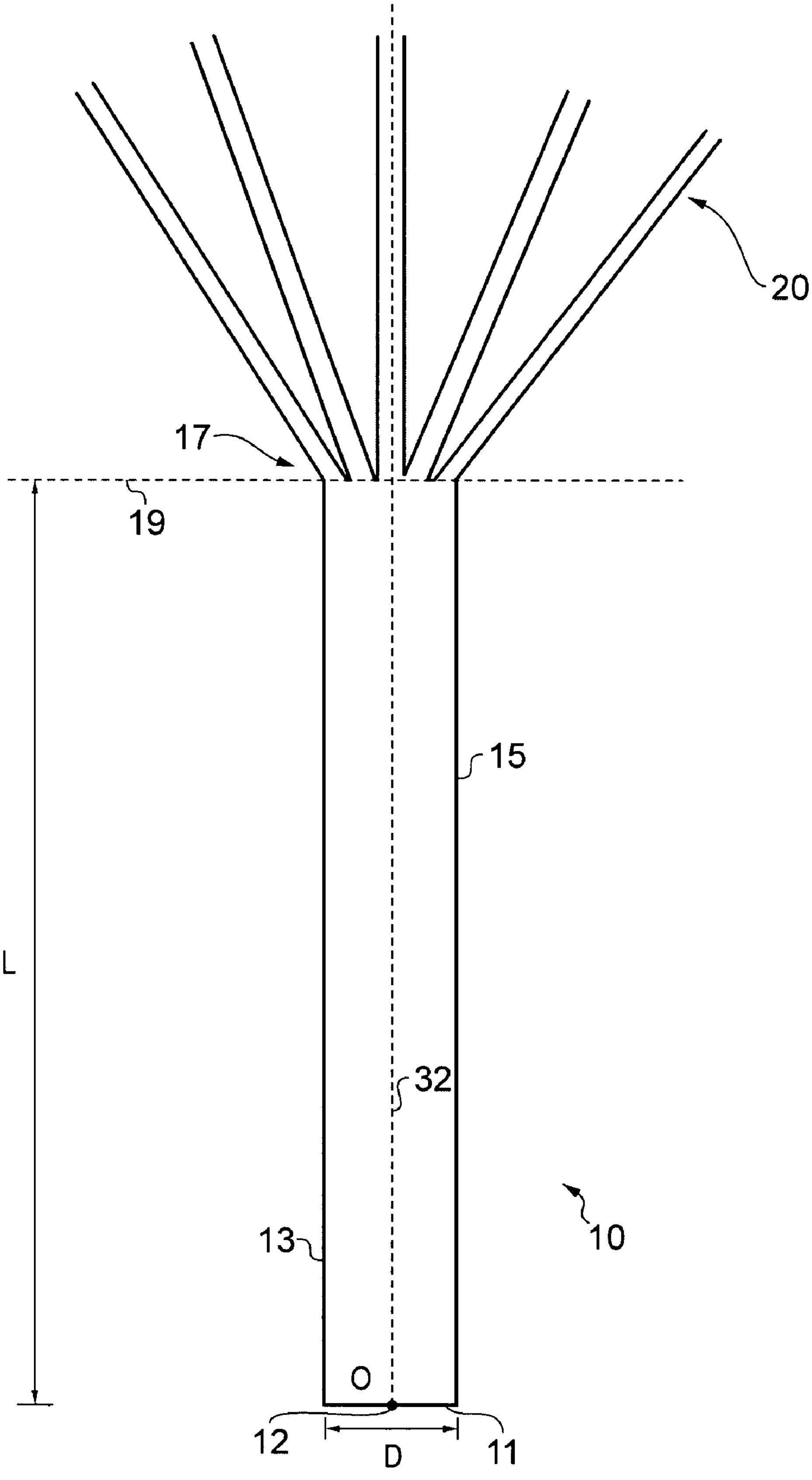


FIG. 3

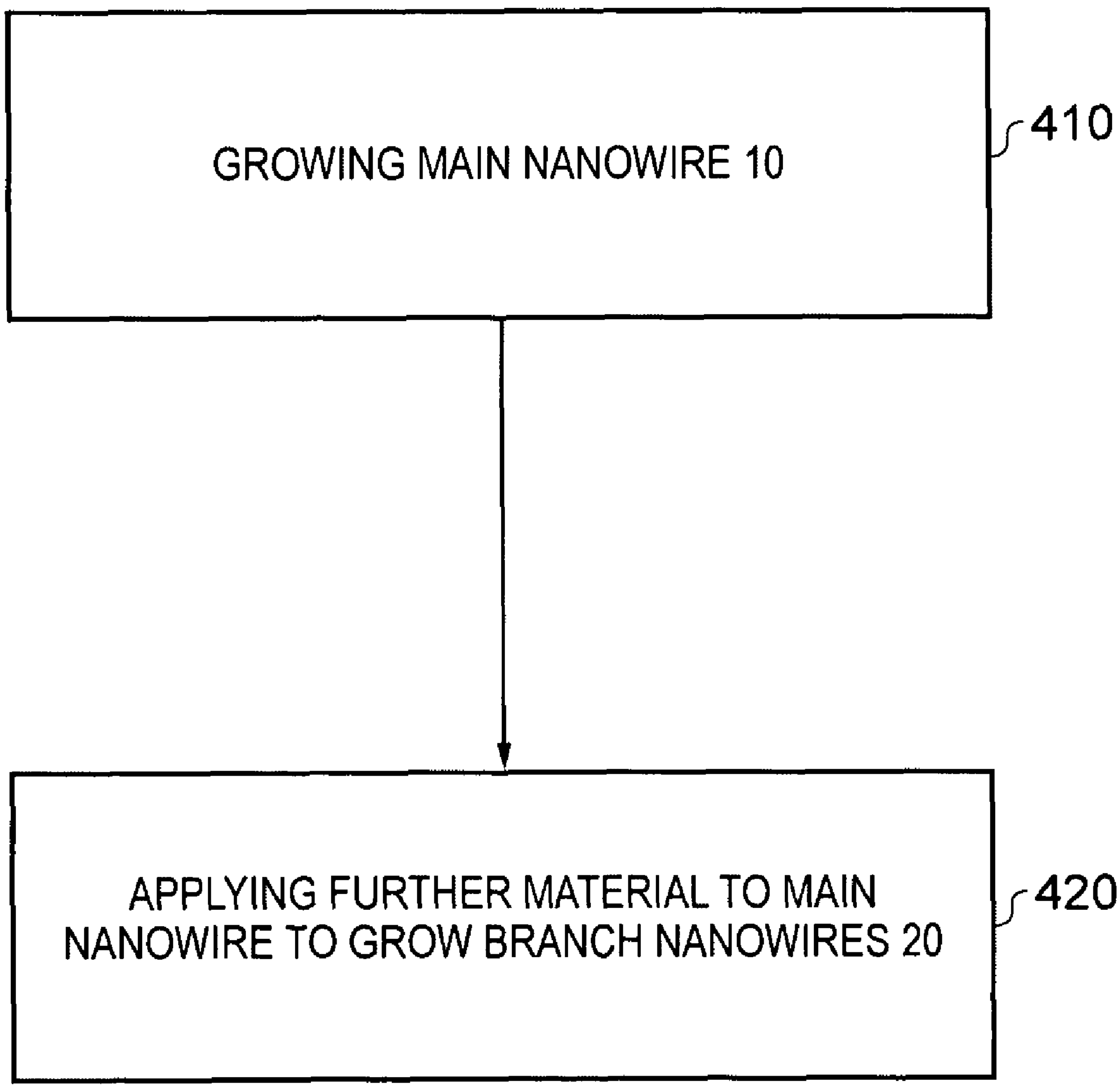
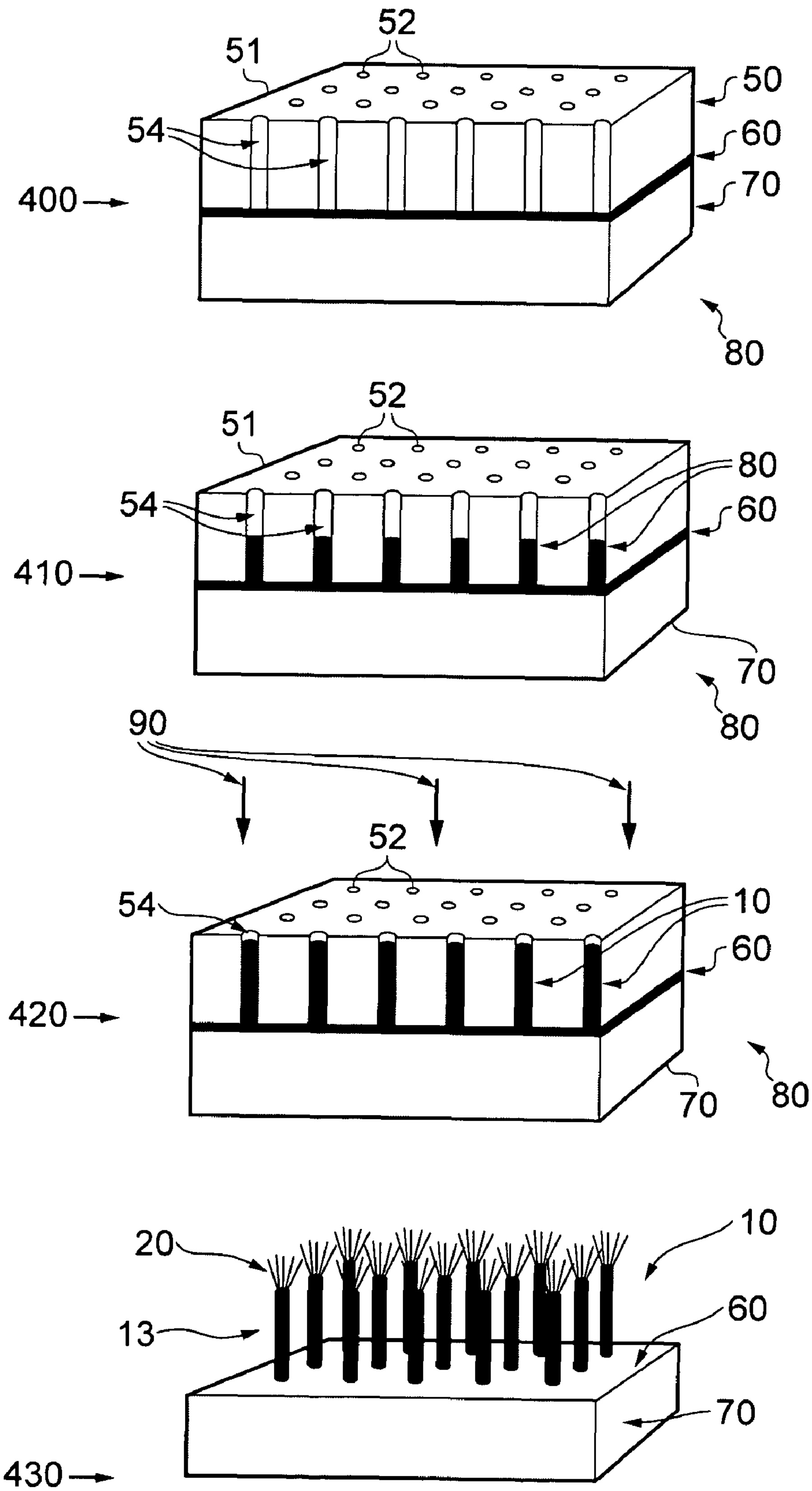

GROWING MAIN NANOWIRE 10
410
APPLYING FURTHER MATERIAL TO MAIN NANOWIRE TO GROW BRANCH NANOWIRES 20
420

FIG. 4


52
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420
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60
13
70
430

FIG. 5

NANOWIRES

FIELD OF THE INVENTION

Embodiments of the present invention relate to nanowires. In particular, they relate to semiconductor nanowire structures.

BACKGROUND TO THE INVENTION

Nanowires are nanostructures that may be used to construct very small scale circuits.

BRIEF DESCRIPTION OF VARIOUS EMBODIMENTS OF THE INVENTION

According to various, but not necessarily all, embodiments of the invention there is provided an apparatus, comprising: a main nanowire having a first portion and a second portion, the first portion having a first carrier concentration and the second portion having a second carrier concentration, different to the first carrier concentration; and a plurality of branch nanowires, each branch nanowire emanating from the first portion of the main nanowire.

The main nanowire may be elongate and have a length. The plurality of branch nanowires may emanate from the main nanowire at a substantially fixed distance along the length of the main nanowire.

The main nanowire may comprise a junction that is substantially perpendicular to the length of the main nanowire. The junction may separate the first portion of the main nanowire and the second portion of the main nanowire.

At least a portion of each branch nanowire may have the first carrier concentration. Each branch nanowire may comprise a junction separating the portion having the first carrier concentration and a portion having a third carrier concentration.

The third carrier concentration may be different to the first carrier concentration and the second carrier concentration. The first carrier concentration, the second carrier concentration and the third carrier concentration may be such that at least one built in potential difference is present across the apparatus.

According to various, but not necessarily all, embodiments of the invention there is provided an apparatus, comprising: an elongate main nanowire having a length; and a plurality of branch nanowires, each branch nanowire emanating from the elongate main nanowire at a substantially fixed distance along the length of the elongate main nanowire.

The substantially fixed distance may be at an end of the length of the elongate main nanowire. Each branch nanowire may emanate from the end of the length of the elongate main nanowire.

The apparatus may further comprise at least one junction separating nanowire portions having different carrier concentrations.

The apparatus may comprise a junction separating first and second portions in the elongate main nanowire having different carrier concentrations.

The apparatus may comprises a plurality of junctions. Each junction may separate a branch nanowire portion having a first carrier concentration and an elongate main nanowire portion having a second carrier concentration. Each junction may be situated at an interface between a branch nanowire and the elongate main nanowire. Alternatively, each junction may be situated at a position away from an interface between a branch nanowire and the elongate main nanowire.

According to various, but not necessarily all, embodiments of the invention there is provided a method, comprising: growing a main nanowire; and applying further material to the main nanowire through an aperture in a mask, in order to grow a plurality of branch nanowires, using the further material, from the main nanowire.

The main nanowire may have a length. The aperture in the mask may enable the further material to be applied to the main nanowire at a substantially fixed distance along the length. The substantially fixed distance may be at an end of the length of the main nanowire.

The main nanowire may be grown by applying material through the aperture in the mask. The mask may restrict how the main nanowire grows. It may be that the mask does not restrict how the branch nanowires grow from the main nanowire. The main nanowire may be grown without using a mask.

A method may further comprise: growing the plurality of branch nanowires, using the further material, from the main nanowire.

The main nanowire may be grown using electrodeposition. The branch nanowires may be grown using a vapor liquid solid process.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of various examples of embodiments of the present invention reference will now be made by way of example only to the accompanying drawings in which:

FIG. **1** illustrates an apparatus and a cylindrical co-ordinate system;

FIG. **2** illustrates a first two-dimensional schematic of an apparatus;

FIG. **3** illustrates a second two-dimensional schematic of an apparatus;

FIG. **4** illustrates a method; and

FIG. **5** illustrates various stages in the growth of an apparatus.

DETAILED DESCRIPTION OF VARIOUS EXEMPLARY EMBODIMENTS OF THE INVENTION

The Figures illustrate an apparatus **10**, comprising: an elongate main nanowire **13** having a length L; and a plurality of branch nanowires **20**, each branch nanowire emanating from the elongate main nanowire **13** at a substantially fixed distance along the length L of the elongate main nanowire **13**.

The Figures also illustrate an apparatus **10**, comprising: a main nanowire **13** having a first portion **18** and a second portion **14**, the first portion **18** having a first carrier concentration and the second portion **14** having a second carrier concentration, different to the first carrier concentration; and a plurality of branch nanowires **20**, each branch nanowire emanating from the first portion **18** of the main nanowire **13**.

FIG. **1** illustrates an apparatus **10**. The apparatus **10** may, for example, be a nanostructure. The nanostructure may be a nanocomponent for use in circuitry. For instance, some or all of the apparatus **10** may be made from a semiconductor material.

The apparatus **10** comprises a main nanowire **13** and a plurality of branch nanowires **20**. The main nanowire **13** and the branch nanowires **20** may be integrally formed.

The main nanowire **13** may be elongate and may, for example, be roughly cylindrical in shape. In the illustrated example, the main nanowire **13** has a smooth, curved outer surface **15**, although this need not be the case. The cylinder has a length L and a diameter/width D. The diameter/width D of the main nanowire **13** may, for example, be somewhere between 300 nanometers (nm) and 1 micron. The length L of the main nanowire **13** may be many times larger than the diameter/width.

FIG. **1** also illustrates a cylindrical co-ordinate system (ρ, ϕ, z) designated with the reference numeral **30**. The z-axis **32** defines a height relative to the origin **12** of the co-ordinate system **30**. ρ defines a radial distance from the z-axis **32**. ϕ defines an azimuth around the z-axis **32**. x and y axes are also shown in FIG. **1** for illustrative purposes. In this example, the azimuth ϕ is measured counter-clockwise from the x-axis.

In this example, the origin **12** of the cylindrical co-ordinate system **30** is considered to be at the centre of a surface **11** at the end of the main nanowire **13** (as shown in FIG. **1**). In this instance, the surface **11** is a face at one end of the length L of the main nanowire **13**. The cylindrical co-ordinate system **30** may be used to define points within or around the apparatus **10**.

Each one of the branch nanowires **20** may emanate from the main nanowire **13** at a substantially fixed distance along the length L of the main nanowire **13**. For example, the branch nanowires **20** may emanate from a segment of the main nanowire **13** that is defined by a substantially fixed value on the z-axis **32** and variable values of ρ and ϕ. Each of the branch nanowires **20** may, for example, have a width/diameter that is somewhere between 2 nm and 100 nm.

In the example illustrated in FIG. **1**, every one of the branch nanowires **20** emanates from a surface **17** at the end of the main nanowire **13**. In this instance, the surface **17** is a face at the end of the length L of the main nanowire **13**. The surface **17** effectively represents an interface between the main nanowire **13** and the branch nanowires **20**.

Each branch nanowire **20** emanates from a different point on the surface **17**. For each of these points, z=L, and ρ and ϕ may take any one of a number of values within the boundary of the surface **17**.

The surface **17** from which the branch nanowires **20** emanate is at the opposite end of the main nanowire **13** to the surface **11** where the origin of the cylindrical co-ordinate system **30** is situated.

In some other embodiments of the invention, some of all of the branch nanowires **20** may not emanate from the surface **17** at the end of the main nanowire **13**. For example, the branch nanowires **20** may emanate from a segment of the main nanowire **13** that is defined by a substantially fixed value on the z-axis that is not equal to L, and variable values of ρ and ϕ. Alternatively, some or all of the branch nanowires **20** may emanate from the outer surface **15** of the main nanowire **13**, at various different points along the z-axis **32**.

FIG. **2** illustrates an example of a two-dimensional schematic of an apparatus **10** having the same form as that illustrated in FIG. **1**. In this example, the main nanowire **13** comprises a junction, which separates a first portion **18** of the main nanowire **13** from a second portion **14** of the main nanowire **13**. The position of the junction is illustrated by a dotted line **16**. In this example, the junction **16** is substantially perpendicular to the length L of the main nanowire **13** and substantially parallel to the diameter/width D and the end surfaces **11**, **17** of the main nanowire **13**.

In this example, each (and every) one of the branch nanowires **20** also comprises a junction. The junctions are illustrated by the dotted line **25** in FIG. **1**. Each junction **25** separates a first portion **22** of a branch nanowire from a second portion **24** of a branch nanowire.

The junctions **16**, **25** in the main nanowire **13** and the branch nanowires **20** may separate semiconductor materials of different types. For example, the first portion **18** of the main nanowire **13** and the first portion **22** of the branch nanowires **20** may be a first type of semiconductor material. The second portion **14** of the main nanowire **13** may be a second type of semiconductor material. The second portion **24** of the branch nanowires **20** may be a third type of semiconductor material.

The first type of semiconductor material may have a first carrier concentration; the second type of semiconductor material may have a second carrier concentration; and the third type of semiconductor material may have a third carrier concentration.

The first, second and third semiconductor materials may have the same "base semiconductor material" (which may be, for example, a group IV semiconductor such as silicon or germanium, or a compound semiconductor including II-VI or III-V semiconductors), but have different levels of doping and/or different dopants. If the first, second and third semiconductor materials have different levels of doping and/or different dopants, the first, second and third carrier concentrations of the first, second and third semiconductor materials are considered to be different.

For example, in some implementations, the apparatus **10** may have a p-i-n structure. In these implementations, the third type of semiconductor material (from which the second portion **24** of the branch nanowires **20** is formed) is a p-type material. The first type of the semiconductor material (from which the first portion **18** of the main nanowire **13** and the first portion **22** of the branch nanowires **20** is formed) is an intrinsic semiconductor. The second type of semiconductor material (from which the second portion **14** of the main nanowire **13** is formed) is an n-type material.

If the apparatus **10** has a p-i-n structure, the junctions **25** in the branch nanowires **20** are p-i junctions and the junction **16** in the main nanowire **13** is an i-n junction.

When the p-i junctions **25** are formed, holes from the p-type material diffuse into the intrinsic material, leaving a depletion region in the p-type material. The depletion region in the p-type material includes negatively charged ions.

When the i-n junction **16** is formed in the main nanowire **13**, electrons from the n-type material diffuse into the intrinsic material, leaving a depletion region in the n-type material. The depletion region in the n-type material includes positively charged ions.

An electric field from the positively charged ions in the n-type material to the negatively charged ions in the p-type material means that the p-i-n structure has a built-in potential.

The p-i-n structure effectively acts as a diode. If the p-i-n structure is forward biased, it conducts electricity, allowing conventional current to flow from the p-type material to the n-type material. Thus, if the apparatus **10** has a p-i-n structure, it may be used as a summation node (to sum signals) in a circuit. Alternatively, if the p-i-n structure is reverse biased, it generally does not conduct electricity.

Alternatively, in other implementations, the apparatus **10** illustrated in FIG. **2** may have an n-i-p structure. In these implementations, the junctions **25** in the branch nanowires **20** are n-i junctions and the junction **16** in the main nanowire **13** is an i-p junction. The n-i-p structure effectively acts as a diode. If the n-i-p structure is forward biased, it conducts electricity, allowing conventional current to flow from the n-type material to the p-type material. Thus, if the apparatus has a n-i-p structure, it may be used as a splitter node (to split signals) in a circuit. Alternatively, if the n-i-p structure is reverse biased, it generally does not conduct electricity.

In further implementations, the apparatus **10** may have a p-n-p structure or an n-p-n structure. In these implementations, the apparatus **10** may act as a transistor, such as a field effect transistor or a bipolar transistor. A controlling electrode may be provided to enable the apparatus **10** to function as a transistor. For example, if the apparatus **10** is configured to function as a field effect transistor, the controlling electrode may be a gate electrode. If the apparatus **10** is configured to function as a bipolar transistor, the controlling electrode may be a base electrode.

FIG. **3** illustrates a further example of a two-dimensional schematic of an apparatus **10** having the same form as that illustrated in FIG. **1**. In this example, the branch nanowires **20** are formed of a first semiconductor material and the main nanowire is formed of a second, different, semiconductor material.

In this example, junctions are present at the interface **17** between each (and every) branch nanowire **20** and the main nanowire **13**. The junctions are illustrated by the dotted line **19**.

In some implementations of the invention, the branch nanowires **20** are made from a p-type material and the main nanowire **13** is made from an n-type material. In these implementations, the p-n structure effectively acts as a diode. If the p-n structure is forward biased, it conducts electricity, allowing conventional current to flow from the p-type material to the n-type material. Thus, if the apparatus **10** has a p-n structure, it may be used as a summation node (to sum signals) in a circuit.

In other implementations, the branch nanowires **20** are made from a n-type material and the main nanowire **13** is made from an p-type material. In these implementations, the n-p structure effectively acts as a diode. If the n-p structure is forward biased, it conducts electricity, allowing conventional current to flow from the n-type material to the p-type material. Thus, if the apparatus **10** has a n-p structure, it may be used as a splitter node (to split signals) in a circuit.

The apparatuses **10** described above in relation to FIGS. **1**, **2** and **3** may have various different applications. For example, the apparatuses **10** may be used in an artificial neural network or any other nanoelectronic architecture (for example, as a summation node) or in nanosensor arrays where the branch nanowires **20** may operate as individual sensors (for example, for the detection of biological or chemical species) and their individual responses are summed together at the interface with the main nanowire.

A method of manufacturing an apparatus **10** in accordance with embodiments of the invention will now be described in relation to FIG. **4** and FIG. **5**.

The first drawing on FIG. **5** (designated with the reference numeral **400**) illustrates a sandwich structure **80** comprising a substrate **70**, a mask **50** and a cathode **60** sandwiched between the substrate **70** and the mask **50**.

The substrate **70** may, for example, be a silicon wafer or a glass slide. The mask **50** may, for example, be a porous membrane such as an anodic aluminum oxide film or a polycarbonate film. The cathode **60** may, for example, be a sputtered or evaporated metal film.

An outer surface **51** of the mask **50** comprises a plurality of apertures/pores **52**. Each aperture **52** defines an elongate chamber **54** that extends through the mask **50** to the cathode **60**.

At block **410** of the method illustrated in FIG. **4**, a main nanowire **13** is grown by applying a material through an aperture in the mask **50**. This is shown illustratively by the drawing that is also designated with the reference numeral **410** in FIG. **5**.

A plurality of main nanowires may be grown using a first growth process. In this example, the first growth process is electrodeposition. A salt compound that comprises a substance to be deposited into the chambers **54** of the mask **50** is dissolved in an electrolyte solution. For example, if one wishes to make main nanowires from silicon, the salt compound is a silicon salt such as silicon tetrachloride ($SiCl_4$). The salt compound is dissociated into its constituent parts (Si^{2+} and $4Cl_4$), in the case of $SiCl_4$) when it is in the electrolyte solution.

The cathode **60** of the structure **80** is one of two electrodes that form part of an electrical circuit. The electrolyte solution contains ions which permit current flow between the two electrodes.

The sandwich structure **80**, comprising the cathode **60**, and the other electrode (the anode) are immersed in the electrolyte solution comprising the dissolved salt compound. When a direct current is applied between the cathode **60** and the anode, the cations in the electrolyte solution (silicon cations in the case of $SiCl_4$) are attracted to the cathode **60**. The cations travel though the apertures **52** in the mask **50** and into the chambers **54** before reaching the surface of the cathode **60**. The cations are reduced at the cathode **60**, and thus deposit in elemental form (with no charge) in the chambers **54** of the mask **50**.

The acquisition of material (silicon, in this case) in the chambers **54** results in a main nanowire **13** being formed in each chamber. Each of the chambers **54** effectively acts to restrict the direction of growth of each main nanowire **13**, such that a desired main nanowire shape is achieved. Each main nanowire **13** may be of the form illustrated in FIGS. **1**, **2** and **3** and described above.

In order to create a doped main nanowire **13** and/or a main nanowire **13** comprising a junction (and two differently doped portions), the salt compound may be varied appropriately or an additional salt may be added to the electrolyte solution.

At block **420** of FIG. **4**, further material is applied to a main nanowire through an aperture in the mask **50**, in order to grow a plurality of branch nanowires, using the further material, from the main nanowire. This is shown illustratively by the drawing that is designated by the reference numeral **420** in FIG. **5**.

The arrows **90** shown in drawing **420** in FIG. **5** illustrate the direction in which the further material is applied to the main nanowires that have been grown in the chambers **54**. In this example, the further material is applied in a direction that is substantially perpendicular to the outer surface **51** of the mask **50**.

As the further material is applied while the mask **50** is still in position around the main nanowires, the deposition of the further material is effectively confined to a particular part of the surface area of each main nanowire. For instance, the geometry of the mask **50** may be such that each aperture enables the further material to be deposited on to a part of the main nanowire **13** that is a fixed distance along the length of the main nanowire **13**. In this example, the deposition is confined to an end surface **17** of each main nanowire (see FIGS. **1**, **2** and **3** and the description above).

The further material may, for example, comprise silicon. In some embodiments of the invention, the further material comprises a catalyst. The catalyst may, for example, be gold. The further material may be applied by sputtering or evaporating a gold film, or depositing metal colloids.

After the further material has been applied to the main nanowires, a plurality of branch nanowires **20** is grown from each branch nanowire using a second growth process. The second growth process may, for example, be a vapor-liquid-solid process. The branch nanowires **20** may be doped and may comprise semiconductor junctions, as described above in relation to FIGS. **1**, **2** and **3**.

The mask **50** may or may not remain in place while the branch nanowires **20** are grown. If the mask **50** is in place, it does not restrict the direction of growth of the branch nanowires **20**. The mask **50** may be removed by wet chemical etching, before or after the branch nanowires **20** are grown.

The branch nanowires **20** grow outwardly from the surface **17** on the main nanowire that the further material is applied to. The final drawing **430** in FIG. **5** illustrates the nanostructures **10** after the vapor-liquid-solid process has taken place and after the mask **50** has been removed. Each nanostructure **10** comprises a main nanowire **13** and a plurality of branch nanowires **20**. Each of the nanostructures **10** may take the one of the forms described above in relation to FIG. **1**, FIG. **2** and/or FIG. **3**.

The above described method advantageously allows a nanostructure **10** to be formed where the each and every one of the branch nanowires **20** of the nanostructure **10** emanates from a particular part of a main nanowire **13** (such as from the end of the main nanowire **13**). This advantageously enables a junction to be defined in the main nanowire **13** that is situated away from the interface between the branch nanowires **20** and the main nanowire **13**, enabling the nanostructure **10** to be used as a summation node or a splitter node.

The illustration of the blocks in FIG. **4** does not necessarily imply that there is a required or preferred order for the blocks and the order and arrangement of the block may be varied. Furthermore, it may be possible for some steps to be omitted.

Although embodiments of the present invention have been described in the preceding paragraphs with reference to various examples, it should be appreciated that modifications to the examples given can be made without departing from the scope of the invention as claimed. For example, it will be appreciated that the method of manufacturing a nanostructure **10** described above is not necessarily the only method of manufacturing that nanostructure.

In alternative methods of manufacture, the main nanowire **13** and the branch nanowires **20** of a nanostructure **10** such as those described in FIG. **1**, FIG. **2** and/or FIG. **3** may be grown using vapor-liquid-solid processes.

In some alternative methods of manufacture it is not necessary to put a mask in place prior to growing the main nanowires **13**. For example, in one alternative method of manufacture, the main nanowires **13** are grown using a vapor liquid solid process without a mask in place. After the main nanowires **13** have been grown, a mask may be put in place, for instance by spin-coating a polymer film and oxygen plasma etching back to expose only the end surfaces of the main nanowires **13**. The further material (for use in the growing branch nanowires **20**) may then be applied to the end surfaces of the main nanowires **13**.

In another alternative method of manufacture, the main nanowire **13** is formed using liquid alloy droplet comprising a metal (such as gold) and a semiconductor (such as silicon). The branch nanowires **20** may be formed by using a temperature change to cause a plurality of solid semiconductor nuclei to form from the liquid alloy droplet. Each solid semiconductor nucleus forms the seed for subsequent growth of a branch nanowire **20**.

In some embodiments of the invention, the junction or junctions in the apparatus **10** may be situated in positions other than those described in relation to FIGS. **1**, **2** and **3**.

As described above, in some embodiments of the invention, the branch nanowires **20** and the main nanowire **13** of an apparatus **10** may be made from the same "base semiconductor material". In some alternate embodiments of the invention, the branch nanowires **20** are formed from a different base semiconductor material to the main nanowire **13**, forming heterostructures. The formation of heterostructures may enable an appropriate band structure to be formed to control/restrict current flow in a particular direction.

Features described in the preceding description may be used in combinations other than the combinations explicitly described.

Although functions have been described with reference to certain features, those functions may be performable by other features whether described or not.

Although features have been described with reference to certain embodiments, those features may also be present in other embodiments whether described or not.

Whilst endeavoring in the foregoing specification to draw attention to those features of the invention believed to be of particular importance it should be understood that the Applicant claims protection in respect of any patentable feature or combination of features hereinbefore referred to and/or shown in the drawings whether or not particular emphasis has been placed thereon.

We claim:

1. An apparatus, comprising:
- a main nanowire having a first portion and a second portion, the first portion having a first carrier concentration and the second portion having a second carrier concentration, different to the first carrier concentration; and
- a plurality of branch nanowires, each branch nanowire emanating from the first portion of the main nanowires;
- wherein at least a portion of each branch nanowire has the first carrier concentration;
- wherein each branch nanowire comprises a junction separating the portion having the first carrier concentration and a portion having a third carrier concentration; and
- wherein the first carrier concentration, the second carrier concentration and the third carrier concentration are such that at least one built in potential difference is present across the apparatus.

2. An apparatus as claimed in claim **1**, wherein the main nanowire is elongate and has a length, and the plurality of branch nanowires emanate from the main nanowire at a substantially fixed distance along the length of the main nanowire.

3. An apparatus as claimed in claim **2**, wherein the main nanowire comprises a junction, substantially perpendicular to the length of the main nanowire, which separates the first portion of the main nanowire and the second portion of the main nanowire.

4. An apparatus as claimed in claim **1**, wherein the third carrier concentration is different to the first carrier concentration and the second carrier concentration.

5. An apparatus, comprising:
- an elongate main nanowire having a length; and
- a plurality of branch nanowires, each branch nanowire emanating from the elongate main nanowire at a substantially fixed distance along the length of the elongate main nanowire;
- further comprising at least one junction separating nanowire portions having different carrier concentrations.

6. An apparatus as claimed in claim **5**, wherein the substantially fixed distance is at an end of the length of the elongate main nanowire, and each branch nanowire emanates from the end of the length of the elongate main nanowire.

7. An apparatus as claimed in claim **5**, wherein the at least one junction separates first and second portions in the elongate main nanowire having different carrier concentrations.

8. An apparatus, comprising:

an elongate main nanowire having a length; and

a plurality of branch nanowires, each branch nanowire emanating from the elongate main nanowire at a substantially fixed distance along the length of the elongate main nanowire;

wherein the apparatus comprises a plurality of junctions, each junction separating a branch nanowire portion having a first carrier concentration and an elongate main nanowire portion having a second carrier concentration.

9. An apparatus as claimed in claim **8**, wherein each junction is situated at an interface between a branch nanowire and the elongate main nanowire.

10. An apparatus as claimed in claim **8**, wherein each junction is situated at a position away from an interface between a branch nanowire and the elongate main nanowire.

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