METHOD PROVIDING RADIAL ADDRESSING OF NANOWIRES

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B82Y 10/00 (2011.01)

U.S. Cl.
H01L 29/0673 (2013.01); B82Y 10/00 (2013.01); H01L 27/10 (2013.01)

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Field of Classification Search
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ABSTRACT

Disclosed is a method to construct a device that includes a plurality of nanowires (NWs) each having a core and at least one shell. The method includes providing a plurality of radially encoded NWs where each shell contains one of a plurality of different shell materials; and differentiating individual ones of the NWs from one another by selectively removing or not removing shell material within areas to be electrically coupled to individual ones of a plurality of mesowires (MWs). Also disclosed is a nanowire array that contains radially encoded NWs, and a computer program product useful in forming a nanowire array.

24 Claims, 12 Drawing Sheets
References Cited

OTHER PUBLICATIONS


* cited by examiner
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<th>Al₂O₃</th>
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### FIG. 13

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### FIG. 14

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<th>TYPE OF DECODER</th>
<th># MWs $\lambda_n$</th>
<th># SHELL TYPES</th>
<th>NW DIAMETER</th>
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**FIG. 16**

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**FIG. 17**
METHOD PROVIDING RADIAL ADDRESSING OF NANOWIRES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 11/883,679, filed on Jun. 10, 2008, now U.S. Pat. No. 8,072,005, issued on Dec. 6, 2011, which is a National Stage filing of PCT/US2006/084128 A2, International Filing date Feb. 2, 2006, which claims priority from U.S. Provisional Application 60/650,449, filed on Feb. 4, 2005 and U.S. Provisional Application 60/729,409, filed on Oct. 21, 2005.

STATEMENT OF GOVERNMENT RIGHTS

This invention was made with government support under grant/contract number CCF-0403674 awarded by the National Science Foundation. The government has certain rights in this invention.

TECHNICAL FIELD

The exemplary and non-limiting embodiments of this invention relate generally to nanotechnology and, more specifically, relate to nanowires (NWs) and to structures and devices that employ nanowires, such as crossbar switches used in, for example, memory elements and programmable logic arrays (PLAs).

BACKGROUND

The various publications that are cited below are incorporated by reference herein.


To read and store data in nanowires requires that individual NWs be addressable. That is, it must be possible to select one NW from each orthogonal set of NWs and apply a voltage to it or pass a current through it. To control NWs from the lithographic level requires that mesoscale wires (MWs) be used to address NWs. However, if each NW is connected to a single MW, the close packing possible with NWs is lost. Thus, schemes are needed that use multiple MWs to control individual NWs.
Several such schemes, referred to as decoders, have been proposed. All assume that NWs are placed at right angles to NWs, as suggested in FIG. 1, where the MWs are labeled $A_{ij}$ and $A_{ij}^c$.

As is explained in further detail below, three types of decoders have been proposed to control MWS. Briefly, the first decoder assumes that gold particles are placed randomly between undifferentiated NWs and MWs. The second assumes that high-K dielectric regions are placed between undifferentiated lightly doped NWs (they can be controlled by electric fields) and MWs. The third assumes that NWs are differentiated during their manufacture by growing lightly doped regions into NWs (modulation doping) that have a length equal to the width of the MWs.

These three methods of addressing NWs that have been developed may be referred to as the randomized contact decoder, the mask-based decoder, and the differentiated NW decoder, respectively.

Two types of axial NW doping patterns, the $\lambda/2\lambda$-hot and binary reflected codes, are described below. The problems that arise in controlling these NWs due to misalignment between doped and undoped NWs are also explored. A question that arises is whether there exist fail-safe doping patterns, namely, those that guarantee that every NW is either “on” or “off”, but not in an ambiguous state as a result of misalignment.

Described now in greater detail are the conventional methods proposed for addressing differentiated and undifferentiated NWs with MWs. Each has associated with it a circuit(s), called a decoder(s), that makes one NW conductive (“turns it on”) and the rest non-conductive (“turns them off”).

The first method of addressing NWs, the randomized contact decoder, assumes that undifferentiated NWs are arranged in parallel. Gold particles are deposited at random between MWs and the NWs with the goal of placing gold particles at about half of the junctions formed by MWs and NWs (see R. S. Williams and P. J. Kuekes, Demultiplexer for a molecular wire crossbar network, U.S. Pat. No. 6,256,767, Jul. 3, 2001). The difficulty of achieving this goal has not been assessed.

Under these assumptions it has been shown that with high probability the randomized contact decoder uses $5 \log_2 N$ NWs to control $N$ NWs. That is, with many MWs, it is possible to select an arbitrary one of $N$ NWs to be conducting and the rest non-conducting.

The second method uses long, undifferentiated NWs. They can be grown using molecular beam epitaxy (MBE) (the SNAP method, see Nicholas A. Melosh et al., Ultrahigh-density nanowire lattices and circuits, Science, 300:112-115, Apr. 4, 2003) or by nanoimprinting (see Michael D. Austin, Hanxiong Ge, Wei Wu, Mingtao Li, Zhaoming Yu, D. Wasserman, S. A. Lyon, and Stephen Y. Chou, Fabrication of 5 nm linewidth and 14 nm pitch features by nanoimprint lithography, Applied Physics Letters, 84(26):5299-5301, Jun. 28, 2004).

FIG. 3 shows a SNAP process to grow NWs by a) forming a superlattice using molecular-beam epitaxy, b) etching away alternating layers in the superlattice, c) depositing metal on the superlattice edges, and d) pressing the metals wires onto an adhesive layer of a chip.

In the SNAP method the superlattice is formed consisting of alternating layers of two materials, such as Aluminum Gallium Arsenide (AlGaAs) and Gallium Arsenide (GaAs). The formed and one type of material, such as AlGaAs, is etched back to create notches. The superlattice is turned and metal deposited on the exposed edges. The superlattice is then pressed onto a chip that contains a thin layer of an adhesive. When removed, long straight NWs are deposited. These NWs have uniform diameter and pitch, unlike the modulation-doped NWs, described below, that are assembled fluidically.

In a nano-imprinting method, a template is grown, perhaps using MBE, and the template is pressed against a soft polymer, thereby creating a contrast pattern in the polymer. Anisotropic etching removes the thin regions, thereby exposing the substrate for doping. The metallic NWs deposited by the SNAP method can also serve the same purpose. If the surface has a thin layer of Si on SiO, which in turn is on a substrate, the SNAP metallic wires can be used with etching to expose Si NWs (see B. Johnston-Halperin et al., Fabrication of conducting silicon nanowire arrays, Applied Physics Letters, 96(10):5921-5923, 2004).

The method proposed to address undifferentiated NWs, referred to as the randomized mask-based decoder (see James R. Heath and Mark A. Ratner, Molecular electronics, Physics Today, 56(5):43-49, 2003), uses lithographically defined rectangular regions of low-K dielectric to shield NWs from the fields associated with NWs. As suggested in FIG. 4, if dielectric regions as small as the pitch of NWs can be produced lithographically, electric fields applied to one of $a_i$ or $a_i', for i \leq \log_2 N$, cause exactly one of $N$ NWs to remain conducting. Here a NW separated from a MW by high-K dielectric acts as a field effect transistor (FET); the application of an electric field of the appropriate strength to the MW immobilizes carriers and drives the conductance of the NW to near zero.

FIG. 4 shows rectangular high-K and low-K dielectric regions that are interposed between vertical MWs and horizontal NWs. The low-K regions shield NWs from the effect of electric fields applied by MWs. When a field is applied to either $a_i$ or $a_i'$ for $i \leq \log_2 N$, exactly one of the $N$ NWs conducts.

Because lithography puts a lower limit on the size of such regions, many randomly shifted copies of the smallest regions are used instead of the increasingly smaller regions. The number of NWs needed to control $N$ NWs with the mask-based decoder has been analyzed (see Eric Rachlin et al. in Procs 2005 Int. Symp. on VLSI, Tampa, Fla., May 11-12, 2005). Under very reasonable assumptions it has been shown that, as NW pitch decreases, at least $2 \log_2 N+46$ MWs will be needed. Although this number is large, the NWs grown with the SNAP process are expected to be much longer and more uniformly spaced than the modulation-doped NWs described next.

The third method, called the differentiated NW decoder, uses NWs that are grown from seed catalysts through a vapor-liquid-solid (VLS) process as depicted in FIG. 5, which shows NWs grown through a vapor-liquid-solid process that are doped as they grow. Reference in this regard can be made to Mark S. Gudiksen, Lincoln J. Lathion, Jianfong Wang, David C. Smith, and Charles M. Lieber, Growth of nanowire superlattice structures for nanoscale photonics and electronics, Nature, 415:617-620, Feb. 7, 2002; Yiyong Wu, Rong Fan, and Peidong Yang, Block-by-block growth of single-crystal Si/SiGe superlattice nanowires, Nano Letters, 2(2):83-86, 2002; and M. T. Björk, B. J. Ohlsson, T. Sasset, A. L. Persson, C. Thelander, M. H. Magnusson, K. Deppert, L. R. Wallenberg, and L. Samuelson, One-dimensional steepneselectric for electronized, Nano Letters, 2(2):87-89, 2002. In an example, silane molecules (SiH$_4$) fall onto gold clusters, precipitating out Si atoms that solidify into crystalline silicon NWs. These NWs can be differentiated by adding dopant molecules to the gaseous mixture as they grow. NWs can be heavily and lightly doped over lengths that are determined by exposure time. This process is referred to as modulation doping when referring to the doping process, and as axial doping when referring to the result.
As stated above, when a MW is placed at right angles to a lightly doped region of a NW and separated from it by high-K dielectric, the MW and NW act as a Field Effect Transistor (FET). The doping levels are chosen so that the same field has no effect on heavily doped regions. One may say that lightly doped regions are controllable, while the heavily doped regions are uncontrollable.

Assume that each NW is given a pattern of controllable and uncontrollable regions, each of the same length. For example, two of four regions could be made controllable, as suggested in FIG. 1, where all six different doping patterns are shown.

Many axially doped NWs with the same doping profile are assembled at the same time and collected in solution. The VLS process is repeated until each of the desired doping profiles is produced. NWs are then assembled on a chip using a fluidic process. NWs with different doping profiles are mixed onto the surface of a fluid where they align them in parallel. NWs are deposited by passing the chip up through the liquid. After drying, lithography is used to trim the NWs deposited in this manner. To produce a crossbar, this procedure is applied again after turning the chip by 90 degrees. Unfortunately, this process cannot guarantee that NWs will have a uniform separation, nor can it guarantee that the boundaries of doped regions will be aligned with one another, or with any point on the chip.

When NWs are placed on a chip, insulation is used to separate the NWs from MWs that are superimposed on them. This combination of NWs and MWs forms an addressing circuit referred to as an encoded NW decoder.

As with the previously described decoders, this decoder exhibits randomness. In this case the types of NW doping pattern that fall on a chip cannot be predicted in advance. Thus, it is necessary to test the chip to discover which NW doping patterns are present. For applications that require deterministic addresses, such as memories, an auxiliary translation memory is then used to translate fixed external addresses into the particular doping patterns that are deposited on the chip during assembly. An important factor affecting manufacturability is the number of different doping patterns, (C), (the size of the code space) that is needed to ensure that all or nearly all of the NWs have different doping patterns.

A discussion is now made of axial doping patterns. Two types of axial codes have been proposed, (h,f)-hot codes (see again André DeHon, Array-based architecture for FET-based, nanoscale electronics, IEEE Transactions on Nanotechnology, 2(1):23-32, March 2003) and length λ binary reflected codes (l-IBC’s). Reference in regard to the latter can be made to Benjamin Gojman et al., Decoding of stochastically assembled nanowire memories, J. Emerg. Technol. Comput. Syst., 1(2):73-108, 2005. To describe them one may assume that controllable NW regions are aligned with MWs (see André DeHon, Patrick Lincoln, and John B. Savage, Stochastic assembly of sub-micron lithographic nanoscale interfaces, IEEE Transactions on Nanotechnology, 2(3):165-174, 2003). FIG. 6 shows an example of modulation-doped NWs encoded with a binary reflected code of length eight.

In a (h,f)-hot code exactly h of the λ regions are controllable. To select one codeword, disabling fields are applied to (λ-h) MWs. The one codeword type whose controllable regions coincide with the MWs to which no field is applied remains conductive.

A λ-IBC has an even number of regions. The doping pattern in the first λ/2 regions is denoted by an arbitrary binary (λ/2)-tuple x (1s,0s) denote controllable (uncontrollable) regions. The doping pattern in the second λ/2 regions is denoted by the Boolean complement of x. A single λ-IBC codeword is selected by applying fields to the MWs that correspond to uncontrollable regions. The one codeword type whose controllable regions coincide with the MWs to which no field is applied remains conductive. The doping patterns for λ-IBC are a subset of the doping patterns of the (h,f)-hot code.

More specifically, shown in FIG. 6 is an example of a binary reflected code with eight controllable or uncontrollable regions that are aligned with MWs. When the second, third, fifth and 8th MWs are turned on, the 1st, 4th, and 7th NWs, all of which have the same doping pattern, become activated, while all others are turned off.

Discussed now is the addressability of modulation-doped nanowires. Using (h,f)-hot codes, DeHon et al. show that with high probability N modulation-doped NWs can be controlled with 2 * log2N + 1 MWs when the design goal is that all NWs doping patterns be different. Using binary reflected codes and the assumption that at least half of the NWs have different doping patterns, Gojman et al. (Decoding of stochastically assembled nanowires, in Procs 2004 Int. Symp. on VLSI. Lafayette, La., Feb. 19-20, 2004) show that this number can be reduced to 2 * log2N + 8 MWs, although a somewhat better upper bound might be obtained for (h,f)-hot codes. They also analyze the area needed for the translation memory.

With regard to the misalignment of axial codes, because fluidic assembly methods cannot control the lengthwise displacement of NWs, alignment between MWs and NW controllable regions cannot be guaranteed (see FIG. 7). To compensate for this problem, doping patterns are repeated along the length of NWs. Even with this accommodation, it remains possible that the overlap between NW controllable regions and MWs will be so small that the control of NWs cannot be definitely guaranteed. That is, a NW may be aligned, but the conductivity of a NW but not effectively turn it off. Such a NW may be said to be in an ambiguous state. The alignment problem is compounded by the difficulty of making sharp transitions between controllable and uncontrollable NW regions during the VLS manufacturing process.

To quantify the effect of misalignment, let Woverlap be the minimal length overlap needed between the field of a mesoscale wire and a NW to reduce the conductivity to a satisfactory level (see FIG. 8). In FIG. 8 the lightly shaded NW region is assumed to be controllable. When the overlap of this region and the electric field is Woverlap or less, the NW cannot be sufficiently controlled.

Let Wpitch be the pitch of MWs. Since all shifts of NWs relative to MWs are equally likely, it follows that the probability, Pcontrol, that a NW is controlled by a MW is Pcontrol = (1-2 * Woverlap/Wpitch), a quantity that is used below to compare NW encoding strategies.

Reference may also be made to U.S. Pat. No. 6,963,077 B2, Sublithographic Nanoscale Memory Architecture, André DeHon, Charles M. Lieber, Patrick D. Lincoln and John E. Savage, that discusses radial modulation doping of NWs in for example, columns 17-19, where the axial doping is etched away in an address window to permit an axial and radially doped NW to be addressed.

SUMMARY

The exemplary embodiments of the invention provide in one aspect thereof a method to construct a device comprised
of a plurality of nanowires (NWs) each comprised of a core and at least one shell. The method includes providing a plurality of radially encoded NWs where each shell is comprised of one of a plurality of different shell materials; and differentiating individual ones of the NWs from one another by selectively removing or not removing shell material within areas to be electrically coupled to individual ones of a plurality of mesowires (MWs).

The exemplary embodiments of the invention provide in one further aspect thereof an array comprised of a plurality of NWs each comprised of a core and at least one shell, where the plurality of NWs comprise radially encoded NWs where each shell is comprised of one of a plurality of different shell materials for differentiating individual ones of the radially encoded NWs from one another by having shells that are selectively removed within areas electrically coupled to individual ones of a plurality of MWs.

The exemplary embodiments of the invention provide in one still further aspect thereof a computer program product embodied on a computer readable medium and comprising program instructions the execution of which results in operations of differentiating individual ones of a plurality of radially encoded NWs from one another by determining a sequence of operations to remove or not remove NW shell material within areas to be electrically coupled to individual ones of a plurality of mesowires (MWs), the operations using a plurality of sequentially applied shell material removal agents, where individual ones of the agents are selected based on their ability to strongly remove one type of shell material but not strongly remove other types of shell material.

BRIEF DESCRIPTION OF THE DRAWINGS

In the attached Drawing Figures:

FIG. 1 shows a conventional crossbar in which NWs in each dimension are addressed by a small set of MWs.

FIG. 2 shows a linear decoding method for an example that employs eight (horizontal) radially encoded NWs.

FIG. 3 shows a SNAP process to grow NWs.

FIG. 4 shows a mask-based decoder for undifferentiated NWs.

FIG. 5 illustrates the growth of NWs.

FIG. 6 shows an example of modulation-doped NWs encoded with a binary reflected code of length eight.

FIG. 7 illustrates an example of NW offset by random amounts from vertical MWs.

FIG. 8 depicts in a side view a method for calculating a probability of loss of control of NWs.

FIG. 9 illustrates the status of NWs as a result of NW misalignment.

FIG. 10 shows the controllability of a pair of MWs as a function of the length of the lightly doped regions.

FIG. 11 illustrates four distinct and exemplary NW shell materials and associated suitable etchants.

FIG. 12 illustrates a logarithmic decoder for eight (horizontal) NWs each having three shells of two types.

FIG. 13 shows the materials etched in each shell under each MW for the decoder of three-shell NWs shown in FIG. 12.

FIG. 14 shows parameters of some radial codes with \(10aC_3 \leq 8.0\).

FIG. 15 illustrates a second portion of a BRC hybrid decoder devoted to radial decoding.

FIG. 16 illustrates parameters of hybrid codes that produce 12 to 32 different NW types (\(C_{\text{MW}}^C_{\text{NW}}\)).

FIG. 17 presents a comparison of axial and radial codes in terms of their effective NW pitch for four different values of \(C_{\text{MW}}\), the code size, for radial codes having \(s=2\) or \(3\) shells and \(\mu=4\) or \(5\) different types of shell material.

FIG. 18 is an enlarged cross-section view of a NW having a core and a plurality of shells disposed about the core.

FIG. 19 illustrates a device that contains a nanowire array that is constructed in accordance with the invention.

FIG. 20 shows a data processor capable of executing a computer program product that is useful in fabricating the radially encoded nanowire array in accordance with the exemplary embodiments of this invention.

DETAILED DESCRIPTION

To cope with misalignment it would be desirable to provide a control strategy having a NW doping pattern and a NW activation strategy so that a NW is either on or off, and not in an ambiguous state. Such a strategy may be referred to as a fail-safe strategy. It is shown, however, that such strategies do not exist. If a strategy is not fail-safe, one may inquire if it is possible to guarantee that misalignment can never result in some NW being on for all applications of fields to NWs (referred to as “on failures”). If such “on failures” exist they may be disastrous, as it would be impossible to control any NWs in the dimension of the crossbar containing such NWs.

In accordance with exemplary embodiments of this invention there is described a radial encoding of NWs and a method of differentiating and controlling NWs using a small set of meso-scale wires (MWs). Such NWs can be used in, as non-limiting examples, crossbars as memories or programmed logic arrays (PLAs). Methods of controlling (decoding) radially addressed NWs and efficient shell etching algorithms for this purpose are disclosed further in accordance with the exemplary embodiments of this invention. The encoding and decoding methods are shown to be comparable in effective pitch with axially encoded NWs, but do not suffer from misalignment errors that are characteristic of such conventional NWs. Also described and analyzed are hybrid axial/radial NW encodings.

In accordance with exemplary embodiments of this invention a fourth type of decoder is described that is competitive with the three conventional decoders in the number of MWs used to control the NWs, but which has the advantage that it is less sensitive to the random displacements produced by stochastic assembly. The decoder in accordance with exemplary embodiments of this invention operates preferably on core-shell NWs (see Lincoln J. Lauhon, Mark S. Gudiksen, Deli Wang, and Charles M. Lieber, Epitaxial core-shell and core-multishell nanowire heterostructures, Nature, 420:57-61, 2002), that is, lightly-doped NW cores to which shells of different types are added. However, variants of the preferred decoder, referred to as the “linear” and “logarithmic” decoders are described below, which differ in the way shells are used to determine which MWs control which NWs.

To illustrate the decoding method in accordance with exemplary embodiments of this invention, an example of the “linear” decoder is shown in FIG. 2, wherein NWs 10 each have three shells with two types per shell. Also shown are a plurality of mesowires (MWs) 12 disposed orthogonally to the NWs 10.

For example, if NWs 10 can have two types of material in the first shell (e.g., a and b) and three in the second (e.g., d, and e), one MW 12 is used for each type of shell encoding (\(M_{D_a}, M_{D_b}, M_{D_d}, M_{D_e}, M_{D_f}, M_{D_g}, M_{D_h}, M_{D_i}, M_{D_j}\) in this non-limiting case). In the region reserved for a particular MW 12 (say \(M_{D_a}\), the one for shell encoding (a,e)), all shells are removed from NWs 10 with that shell encoding, but one insulating shell remains over all other NWs. When an immo-
error in the BRC decoding of the entire frame. This is because the BRC decoding is performed on the entire frame and not on individual symbols. If the decoding error occurs in the middle of the frame, it will affect the symbols at both ends of the frame, resulting in a higher overall error rate. However, if the error occurs in the middle of a symbol, it will only affect that symbol and not the entire frame. Therefore, the probability of an error occurring in the middle of a symbol is lower than the probability of an error occurring in the middle of the frame.

5. The BRC error detection code provides a high level of error detection capability, which allows the system to detect and correct errors before they become too significant. This is important in a system where data integrity is crucial, such as in telecommunications and computer networks. The BRC code is designed to detect errors in the transmission of data, and it can help to ensure that the data is transmitted accurately and reliably.

6. The BRC error detection code is relatively simple and easy to implement, which makes it ideal for use in a variety of applications. It is a low-cost solution that can be used in many different environments, including in communication systems, storage systems, and computer networks. The simplicity of the BRC code allows it to be used in a wide range of applications, making it a versatile and valuable tool for data transmission.

7. The BRC error detection code is known for its robustness, which means that it can handle a wide range of error conditions. This is important in a system where data integrity is crucial, as it allows the system to continue to function even when errors occur. The BRC code is designed to handle a variety of error conditions, including single-bit errors, burst errors, and random errors, making it a reliable and effective tool for data transmission.

8. The BRC error detection code is a low-cost solution that can be implemented in a variety of applications. It is an efficient and effective way to detect and correct errors in the transmission of data, which makes it a valuable tool for data transmission. The simplicity and robustness of the BRC code make it an ideal choice for a wide range of applications, including in communication systems, storage systems, and computer networks. The low cost and efficiency of the BRC code make it a popular choice for data transmission.
Definition: A code is a set of activation patterns with the property that no activation pattern ambiguously activates a set of NWs, and the sets of NWs that are activated are disjoint.

A discussion is now made of radically coded nanowires. Core-shell NWs are assembled by adding shells to NWs with lightly doped cores (see Launon et al., Epitaxial core-shell and core-multishell nanowire heterostructures, Nature, 420: 57-61, 2002). The sequence of shell materials grown around a NW core is referred to herein as its radial encoding. In accordance with exemplary embodiments of this invention, radial encodings are employed to differentiate and control NWs.

Axial NW growth occurs when reactant activation and addition occurs at the catalyst site (e.g., the gold cluster in Fig. 5) and not on the NW surface. Radial NW growth occurs under conditions where the reaction proceeds favoring homogeneous vapor phase deposition on the NW surface. Multiple shells of nearly arbitrary composition are possible, although exceptional growth of these shells requires consideration of lattice structures.

There are a number of possible core/multi-shell nanowire heterostructures that could be prepared using atomic layer deposition and/or chemical vapor deposition methods such that the shell could be selectively etched. Two specific and non-limiting cases in which etching is carried out using ‘dry’ reactive-ion etching (RIE) and ‘wet’ chemical etching are as follows. First, a core/multi-shell nanowire heterostructure composed of silicon (Si) core, a zirconium oxide (ZrO2) inner shell, and aluminum oxide (Al2O3) outer shell can be selectively etched by RIE. Using low energy argon ion (Ar+) RIE (e.g., see M. E. Dwyer, M. Dellino, S. Salminen. Low energy ion etching of aluminum oxide films and native aluminum oxide. Journal of Applied Physics, 72: 5467-5470, 1992), the Al2O3 can be selectively etched with little or no effect on ZrO2 (e.g., see Yuri Ledebinski, Andrei Zenkevich. Silicide formation at HfO2-Si and ZrO2-Si interfaces induced by Ar+ ion bombardment. Journal of Vacuum Science & Technology A, 22: 2261-2264, 2004) or the lithography polymer resist (e.g., see Y. Koval. Mechanism of etching and surface relief development of PMMA under low-energy ion bombardment. Journal of Vacuum Science & Technology B, 22: 843-851, 2004). Subsequently, the ZrO2 could be selectively etched to the Si nanowire core using BCl3/Cl2 RIE for energies between 21 eV and 28 eV (e.g., see L. Sha, J. P. Chang. Plasma etching selectivity of ZrO2 to Si in BCl3/Cl2 plasmas. Journal of Vacuum Science & Technology A, 21: 1915-1922, 2003). Second, a core/multi-shell nanowire heterostructure composed of a Si core, a ZrO2 inner shell, and a germanium (Ge) outer shell may be readily prepared and etched by wet chemical methods. Specifically, Ge can be selectively etched with respect to ZrO2 using a simple hydroperoxide solution (e.g., see Boris W. Baternan. H10PO4 soaks, pits, and etch rate in germanium crystals. Journal of Applied Physics, 28: 1236-1241, 1957) that only dissolves Ge but has no effect on ZrO2 or the lithography polymer resist (Faraj A. Abu-Illa, Mansor B. Ahmad, Nor Azawwa Ibrahim, Mohamad Zaki Ab Rahman, Khatirul Zaman Md. Dahan, Wan Md. Zin Wan. Yunus, Graft copolymerization of methyl methacrylate onto rubber-wood fiber using H2O2 and Fe2+ as an initiator system. Journal of Applied Polymer Science, 88: 2499-2503, 2003).

Assume now that core-shell NWs are produced with n shells. A core-shell, or radially encoded NW 10, is controlled with a MW 12 as follows:

a) Under the future location of the MW 12, etchants selectively remove the NW’s shells, exposing its lightly-doped core.

b) Insulation is deposited over the exposed core.

c) The MW 12 is deposited over the insulation, where the NW/MW junction forms a FET.

d) A set of such junctions is referred to as a radial decoder (see FIG. 2) if, for each NW encoding, they allow only NWs with that encoding to be made conducting. Two types of radial decoders, “linear” and “logarithmic,” are discussed in further detail below.

Core-shell NWs 10 have at least one important advantage: they are substantially insensitive to random lengthwise displacement, unlike modulation-doped NWs. As a consequence, core-shell NWs 10 cannot be in an ambiguous state of conduction due to misalignment of NWs 10 and MWs 12. Furthermore, when a core-shell NW is deposited over exposed cores, the NW 12 will self-align with them (see Lance A. Glasser and Daniel W. Dopperpulh, The Design and Analysis of VLSI Circuits, Addison-Wesley, Reading, Mass., 1985), thereby obtaining far superior registration between controllable NW regions and MWs than can be obtained with modulation-doped NWs.

It can be noted that with the use of core-shell NWs 10 the addition of shells increases the diameter and the spacing between NWs, thereby reducing the available area. However, additional NWs do not have to be added to account for the fact that some NWs are in an ambiguous state due to misalignment. Furthermore, NWs appear to be more tolerant of variations in the manufacturing process and are compatible with other methods of controlling NWs.

Creating a radial decoder employs a selective shell removal process, such as an etching process, that exposes the cores of NWs 10 with a particular type of radial encoding, while leaving other cores insulated. To allow for this particular selective shell removal process to occur, the shell materials must be sufficiently different that an etch for one type of shell material has little or no effect on another type of shell material.

There are a number of possible core/multi-shell nanowire heterostructures that may be prepared using atomic layer and/or chemical vapor deposition (CVD) methods such that multiple shells can be selectively etched. Four distinct exemplary and non-limiting shell materials are highlighted in FIG. 11, namely, Cu, Al₂O₃, GaSb, and InAs, along with specific wet etching solutions (FeCl₃, NaOH, C₆H₅KNaO₄+HCl+H₂O₂+H₂O and C₆H₅H₂O₄+H₂O₂) that are capable of differentiating any of the materials from another as required to implement the decoder. Individual ones of the etchants are selected based on their ability to strongly etch one type of shell material but not strongly etch other types of shell material. For example, C₆H₅KNaO₄+HCl+H₂O₂+H₂O is assumed to be for this example to strongly etch GaSb, but not strongly etch InAs.

In FIG. 11 four exemplary types of shell material for the core-shell NW 10 are shown on the left. Each is assumed to include, by way of example and not as a limitation, a silicon (Si) core, a hafnium oxide shell (HfO₂, i.e., a high-K dielectric), and outer shells made of one of four materials. The columns list the effect of etchants on the outer shells. The etchants in the two right columns etch both InAs and GaSb. The third etchant etches GaSb 15 times faster than InAs, while the fourth etchant etches InAs 100 times faster than GaSb. Reference in this regard can be made to Oliver Dier, Chun Lin, Markus Grau, and Markus-Christian Amann, Selective and non-selective wet-chemical etchants for GaSb-based materials, Semiconductor Science and Technology, 19(11):1250-1253, 2004.

Referring briefly to FIG. 18 there is shown an enlarged cross-section view of a NW 10 having a core 11A, a high-K dielectric shell 11B (e.g., one formed from HfO₂) and a plurality of shells 11C, 11D, 11E (for a non-limiting case of three shells) disposed about the core 11A and the dielectric shell 11B. A given NW 10 may have more or less than the three shells 11C, 11D, 11E shown in FIG. 18.

A specific implementation includes at least two specific features. First, the integral high dielectric constant (high-K) shell 11B of, for example, HfO₂ is deposited over the core 11A using, for example, CVD prior to the growth of the selectively etchable shells 11C, 11D, 11E to simplify the overall fabrication process. The high-K dielectric shell 11B increases the coupling between the NWs 10 and the controlling MWs 12. Second, the first shell 11C outside of the high-K dielectric shell 11B is made thicker than subsequent shells to ensure sufficient differential gate response of the MWs 12 in contact with the high-K dielectric on the inner shell 11B.

In the discussion of the radial decoders it is assumed that each shell 11C, 11D, 11E of each NW 10 can be made from any one of a independently selectively removable (e.g., etchable) materials. Herein a notation is employed where materials are m₁, . . . , mₚ and Etch(mᵢ, W) refers to the etching procedure that removes just material mᵢ from the region under MW W. Writing [Etch(mᵢ, W), . . . , Etch(mₚ, W)] means that Etch(mᵢ, W) is followed by Etch(mᵢ₋₁, W), . . . , Etch(m₁, W). For an arbitrary set of materials, M, writing Etch(M, W) means that for all mₑM, all Etch(mₑ, W) are applied sequentially in some arbitrary order.

In a radial encoding the innermost shell material (11C) is listed first. In an etching sequence, operations on the outer shell (e.g., 11E, as in FIG. 18) appear first. Thus, if NWs Nₛ and Nₓ have radial encodings (mₛ) and (mₓ) respectively, the sequence [Etch(mₓ, W), . . . , Etch(mₛ, W)] exposes the core 11A of NW, under MW W, but only removes the outer shell 11E of NW. A MW W can then control NW without affecting Nₓ.

Described now is the linear decoder for multi-shell radial codes. In general, a radial decoder allows a set of MWs 12 to control NWs manufactured with some set of radial encodings. Consider a family F of radial encodings in which each possible encoding uses n shells, and each shell is one of at least 1 possible materials. In order to ensure that shells can be removed one at a time under one MW 12, assume that two consecutive shells are not composed of the same material. When manufacturing a NW 10, the first shell can be of any of α types, but each additional shell must be a different type, which implies that N=α(α−1)(α−2) . . . 1. This means that four independently etchable materials and two shell layers can lead to 12 different shell encodings. If five independently etchable materials are used, 20 shell encodings can be generated with two shells, and 80 encodings with three shells.

Given an arbitrary family of radial encodings F, a linear decoder uses a separate MW 12 for each radial encoding. If MW Wᵢ is associated with encoding Eᵢ(mᵢ₋₁, . . . , mᵢ), then one can apply

\[\text{Etch}(mᵢ₋₁, Wᵢ), \text{Etch}(mᵢ₋₂, Wᵢ), \ldots, \text{Etch}(m₁, Wᵢ)\]

This etching sequence exposes the cores 11A (note that the high dielectric shell 11B is still present) of NWs 10 with encoding Eᵢ, under Wᵢ. The cores of NWs 10 with other encodings remain unexposed, since for these NWs 10 at least one etching step will fail to remove a shell. Each of the 2ᴺ−1 F
MWs 12 can turn off exactly the NWs 10 with a particular radial encoding. The decoder shown in FIG. 2 is a linear decoder.

Note that the linear decoder etches each material in each shell under each MW 12. Thus, it performs n λR ε etching operations, where n is the number of shells and λR ε is the number of MWs 12 (with an equal number of masking and unmasking operations). This value can be reduced to λR ε etching operations by observing that the etching operations under each MW 12 that remove the same material can be done together after first masking all other MWs 12 from etchants and unmasking these regions when finished.

Lemma: The linear NW decoder for N=α(α−1)−1 NW types containing n shells of a type can be implemented using λR = 2 [log2α] MWs. The restriction prevents every possible shell material from appearing in each shell, but allows for more powerful etching operations.

The α=|F| shell materials are divided into two disjoint sets of size αt and αs=αt+α−α. The materials used to form the ith shell of each radial encoding is chosen from the first set when i is odd, and from the second set when i is even. This allows for N=αt[n−1][n+2] possible encodings, which implies that N=α(α−1)/2 when n is even.

Let αt denote the materials that can appear in the ith shell. αt simply depends on the parity of i. Let M be an arbitrary set of materials. When no other etchings have been done, [Etch(αt, W), Etch(αt, W), ..., Etch(αt, W)] will remove the outermost n−αt shells of every NW in the region under W. Etch(M, W) then removes a shell from only NWs with a material in M in their ith shell. [Etch(αt−1, W), ..., Etch(αt, W)] then exposes the cores of these NWs. Denote this entire three-part procedure as LayerEtch(M, W, s).

The restriction on F ensures that αt and αt−1 are disjoint and that Etch(αt, W) does not remove more than one shell at a time. This implies that LayerEtch(M, W, s) can only expose the cores of NWs that are affected by the Etch(M, W) operation. LayerEtch(M, W, s) thus exposes the cores of exactly those NWs with a material in M in their nth shell.

The procedure LayerEtch(M, W, s) can be applied to any sets M of materials in the nth shell that are used by an etching procedure. In particular, it can be used with the etching procedure for the linear or logarithmic decoder on one shell. When the shell etching procedure is linear (logarithmic), the decoders resulting from these procedures may be referred to as LinearLog and FullyLog, respectively. The two decoders, which are the same when |F|=2, are illustrated in FIG. 12.

More specifically, reference can be made to FIG. 12 for showing a logarithmic decoder 20 for eight (horizontal) NWs 10 each having three shells of two types. The insulated core of a NW is exposed to the field on a MW 12 if the NW 10 has a particular type of material in a particular shell. Applying an immobilizing field to one of the (vertical) NWs 12 labeled αt and αs causes one half of the NWs 10 to have very high resistance. The three shaded rectangles below MWs 12 indicates which shell material(s) is (are) removed in each shell; the top rectangle corresponds to the outer shell. If two types of shading occur in a rectangle, both materials in a shell are removed. Otherwise only one type is removed.

A discussion is now made of the FullyLog decoder. In etching for the FullyLog decoder the set M assumes values Mαt or Mαs, as defined above. Thus, the FullyLog decoder uses:

\[ M_{\text{LayerLog}} = \sum_{i=1}^{n} [\log_2 \alpha_i] \text{LayerLog}. \]

Since \[ |\alpha_i| = \alpha_t \]
when s is odd, and \[ |\alpha_i| = \alpha_s \]
when s is even,

\[ M_{\text{LayerLog}} = 2 |\alpha| \sum_{i=1}^{n} [\log_2 \alpha_i]. \]

Consider now the number of operations that are needed to expose NWs to MWs. Let \( W_t^L \) be the th MW corresponding to the nth shell. It follows that FullyLog requires \( |\alpha_i| \) etching steps under this MW in the nth shell for s is for a total of \( T=|\alpha_i| \) operations, where \( T=\sum_{i=1}^{n} |\alpha_i| \). There are \( 2 |\log_2 \alpha_i| \) MWs corresponding to the nth shell and they require \| \alpha_i |[\log_2 \alpha_i] \) additional etching operations. Thus, FullyLog performs \( 2 T \sum_{i=1}^{n} [\log_2 \alpha_i] \) operations.

A discussion is now made of decoders for multiple-shell radial codes. In order to extend the logarithmic radial decoder to multiple shell encodings, the encodings in F are restricted.
It can be seen that the FullyLog etching procedure implements NW decoders for N\(\times n\) types with n shells using O(n\(^2\)) etching steps. Faster algorithms can be implemented by performing operations in parallel.

As with previous decoders, the FullyLog decoder can be implemented with fewer etching steps when they are done in parallel. As suggested in FIG. 13, they can be performed in \(\Sigma_{\alpha_n} \alpha_n\) etching operations.

FIG. 13 shows the materials etched in each shell under each MW 12 for the decoder of three-shell NWs 10 shown in FIG. 12. Shell types r and g are used in the outer and inner shells and b and y are used in the inner shell. The etching procedure exposes under MW \(W_r\) with cores of NWs that have material t in shell s. For example, under \(W_r\), the cores of NWs are exposed that have type b in the middle shell. Etching begins with the first or outer shell. The FullyLog procedure operates on one column at a time. All but one column is exposed at a time and all cells in that column are removed in sequence. For example, under \(W_g\), it removes shells of type r (g) followed by both types of shell in successive shells. This procedure executes 36 etching steps. A fast version of the FullyLog procedure etches all cells in one row in parallel in one step except for the cell in the one column that is masked. For example, it removes outer shell of type r under all NWs except for \(W_r\). It then removes all shells of type g under all NWs except for \(W_r\) etc. This faster procedure executes six etching steps.

Theorem: The FullyLog decoder for n-shell NWs having \(\alpha_1, \alpha_2, \ldots, \alpha_n\) materials in odd (even-indexed) shells and N-\(\alpha_1\) \(\alpha_2\) NW types can be implemented with \(M_{\text{FullyLog}} = \frac{2 \times \log_2(n+2)}{\log_2(n+2)} + \frac{\log_2(n+2)}{\log_2(n+2)}\) MWs, and \(E = \frac{n+2}{2} \alpha_2 + \frac{n+2}{2} \alpha_1\) etching operations. When \(\alpha_1 = \alpha_2 = \alpha_2\) and n is even, \(N = \alpha_2\), \(M_{\text{FullyLog}} = \frac{2 \times \log_2(n+2)}{\log_2(n+2)}\) and \(E = \log_2(n+2)\).

A discussion is now made of the LinearLog decoder. In etching for the LinearLog decoder the set M for the ith shell assumes the value of one shell material at each MW. Thus, the LinearLog uses \(M_{\text{LinearLog}} = \Sigma_{\alpha_n} \alpha_n\) MWs. Since \(\alpha_1 = \alpha_2\)...

When s is even, \(M_{\text{LinearLog}} = \frac{n+2}{2} \alpha_2 + \frac{n+2}{2} \alpha_1\). In some cases \(M_{\text{LinearLog}}\) is smaller than \(M_{\text{FullyLog}}\). For example, when \(\alpha_1 = \alpha_2 - 3\) and n = 2, \(M_{\text{LinearLog}} = 6\) whereas \(M_{\text{FullyLog}} = 8\).

Consider now the number of operations that are needed to expose NWs to MWs. As with the FullyLog decoder, the LinearLog decoder under MW \(W_r\), requires \(T(\alpha_n)\) operations on shells other than the s th, where \(T = \Sigma_{\alpha_n} \alpha_n\), and one operation on the s th shell for a total of \(F_{\text{LinearLog}} = T + \Sigma_{\alpha_n} \alpha_n\) operations. This is quadratic in n, the number of shells.

As with previous decoders, the LinearLog decoder can be implemented with \(\Sigma_{\alpha_n} \alpha_n\) etching operations.

Theorem: The LinearLog decoder for n-shell NWs having \(\alpha_1, \alpha_2, \ldots, \alpha_n\) materials in odd (even-indexed) shells and N-\(\alpha_1\) \(\alpha_2\) NW types can be implemented with:

\[M_{\text{LinearLog}} = \frac{n+2}{2} \alpha_2 + \frac{n+2}{2} \alpha_1\]

and

\[E = \frac{n+2}{2} \alpha_2 + \frac{n+2}{2} \alpha_1\] etching operations. When \(\alpha_1 = \alpha_2 = \alpha_2\) and n is even, \(N = \alpha_2\), \(M_{\text{LinearLog}} = n \alpha_2\), and \(E = \log_2(N)\).

A discussion is now made of code discovery and faults. Recall in this regard that codewords are randomly assigned to NWs in a nanoscale. As a result a discovery process is required to determine which encodings are present. All radial decoders described above allow for the use of the efficient code discovery algorithm given in, as a non-limiting example, one found in Benjamin Gojman, Eric Rachlin, and John B.


The etching processes described above may behave imperfectly. Shells which should remain may be removed, and shells that should be removed may remain. Either error can alter the subset of active NWs that control a NW. In the nanoscale a binary tuple is assigned to each NW in which a 1 corresponds to NWs that turn NWs on, and a 0 corresponds to NWs that do not influence the NW. Etching errors can flip the bits in this tuple.

In order to protect against an occurrence of a bit flip, the tuples associated with core-shell NWs preferably have a sufficiently high Hamming distance. This may be readily accomplished with a minor modification to the single shell logarithmic etching procedure. Instead of associating arbitrary binary strings with shell materials, one may instead use coding theory to assign binary strings with a sufficiently high Hamming distance. As is explained in Philip J Kuekes, Warren Robinett, Gabriel Seroussi, and R Stanley Williams, Defect tolerant interconnect to nanoelectronic circuits, Nanotechnology, 16:869-882, 2005, NW tuples with a Hamming distance of 2d+1 can tolerate up to d errors.

When this concept is extended to the FullyLog decoder, binary tuples with a Hamming distance of 2d applied to each shell allow for up to d errors to be tolerated across n shells. A discussion is now made of two-stage etching. The unknown codewords present at each ohmic contact (OC) must be discovered and recorded in programmable address translation circuitry. If the codewords at each OC can be made the same, the size of the address translation circuitry could be dramatically reduced. The use of core-shell NWs make this possible.

More specifically, when the nanoscale is first etched, the resultant decoder can be used to discover which codewords are present at each OC. If each OC has at least one codeword, the regions under a second set of C NWs can be etched to form a second linear decoder. At each MW, at each OC, one would select an etching process that exposes one of the C shell type sequences known to be present. Each of the C NWs is then guaranteed to control at least one NW at each OC. When the new decoder is used, each OC contains each codeword, and programmable address translation circuitry is no longer needed.

Two-stage etching can create a deterministic linear decoder if C distinct shell type sequences are present at each OC. After codeword discovery, a custom etching process is used to ensure each of C MWs controls one of C NWs.

It has been discovered that an arbitrary assignment of NWs to MWs can be achieved if the C sequences present meet an additional criteria. Let S be the set of shell sequences present at a particular OC. Assume that there are C sequences in S such that each sequence contains a shell type in some shell that no other sequence in S contains in that shell. If this condition is met, C arbitrary codewords can be deterministically assigned.

Core-shell NWs eliminate misalignment and provide an elegant means of fault tolerance. Two-stage etching, though possibly more time-consuming, assigns NW codewords deterministically. This eliminates the need for programmable address translation circuitry. It also allows nanoscale to compute functions, since each NW computes the NOR of a set of NWs.

Non-limiting examples of radial codes are now provided. Consider the number of different NW types needed to ensure that N NWs can be addressed with high probability. In FIG. 3 it is assumed that N NWs in each dimension of the crossbar...
are connected to one ohmic region at each end. As is shown in DeHon et al., Stochastic assembly of sub lithographic nanoscale interfaces. IEEE Transactions on Nanotechnology, 2(3): 165-174, 2003, to ensure that all or most of the N NWs in each dimension are different with high probability requires that the number of differently encoded NWs, C_p, be enormous. Thus, assume that the ohmic region at one end of the NWs in each dimension is subdivided into m ohmic regions each containing w NWs (also shown in DeHon et al., cited above).

The diameter and pitch of radially encoded NWs grows with the number of shells. Thus, it is desirable to keep the number of shells to a reasonable minimum. In turn, the number of shells is related to C_p, the size of the code space. If the number of differentially etchable shell materials is small, the number of shells must be large to meet a minimum requirement on C_p.

One may then inquire as to how large C_p must be to ensure that with probability 0.99 or larger at least half of the NWs in each dimension of an array has a unique address specified by its ohmic region and NW type within that region. Both analysis (Benjamin Gojman, Eric Rachlin, and John B. Savage. Evolution of design strategies for stochastically assembled nanoarray memories, J. Emerg. Technol. Comput. Syst., 1(2): 73-108, 2005) and empirical evidence (Eric Rachlin and John B. Savage. Small codespace addressing strategies for nanoarrays, Nano Note 3, Computer Science Department, Brown University, 2005) indicate that it suffices to have a range of about 10^6C_p<300. More generally, the range may be from about 2SC_p^3x, where x can be large. Shown in Fig. 14 are examples of radial codes that meet these requirements.

More specifically, FIG. 14 shows parameters of some radial codes with 10^6C_p<300. Here n is the number of shells and λ_p is the number of NWs. The distribution of shell types is shown in the third column. The type of decoder is shown in the fourth column. The minimal number of types of shell materials that suffice to encode NWs, is shown in the sixth column (see the discussion above related to shell etching). The last column contains the diameter of NWs (and their pitch when abutted one against the other) under the assumption that cores have a diameter of about 5 nm and each shell adds about 4 nm to the diameter.

Discussed now are hybrid NW codes and decoders. A NW is considered to have a hybrid encoding if its core has an axial encoding and its shells have a radial encoding. To cope with random axial displacement of NWs, the axial encoding is repeated along the length of NWs.

It is now shown how an axial and radial decoder can be efficiently combined to form a hybrid decoder. An exemplary BRC hybrid decoder uses two sets of NWs. The first set functions as an axial decoder, the other as a radial decoder. The total number of NWs required by the hybrid decoder is proportional to the sum of the number of NWs required by the axial and radial decoders when used separately.

The BRC hybrid decoder may be designed to work exclusively with binary reflected codes. Recall that in λ_p-BRC the doping pattern is a repeated sequence of λ_p, heavily or lightly doped regions. The repeated sequence is such that the first λ_p/2 regions are the complement of the second λ_p/2 regions. If two regions in the sequence lie λ_p/2-1 regions apart, exactly one will be lightly doped. The radial decoding portion of the BRC hybrid decoder relies on this characteristic.

Consider a radial code controlled by a radial decoder using λ_p NWs. Assume that the radial code is used in conjunction with a λ_p-BRC to generate hybrid NWs. A BRC hybrid decoder is constructed as follows:

a) Use λ_p consecutive NWs for axial decoding. Under these NWs, all shells are removed from all NWs. The NWs then function as a standard axial decoder. The λ_p NWs are used to select hybrid NWs with a given axial codeword. In other words, the NWs can make non-conducting all NWs that do not have a particular binary reflected codeword.

b) Use 2λ_p NWs for radial decoding. Each NW contains a repeated binary reflected codeword. If a pair of NWs are λ_p/2-1 regions apart, exactly one will lie over a lightly doped region. Use λ_p such pairs (in [2λ_p/λ_p] repetitions of the axial code) to produce two identical radial decoders. Apply the same etching operations to both NWs in a pair.

c) One NW in each pair is adjacent to an exposed lightly doped region. If the two radial decoders are used simultaneously, they successfully simulate a standard radial decoder. The two λ_p NWs can thus select NWs with a given radial codeword. When a radial and axial codeword are selected simultaneously, only NWs with a particular hybrid codeword will remain conducting.

As was mentioned above, [2λ_p/λ_p] repetitions of an axial λ_p-BRC codeword suffice to implement a radial code. Thus, λ_p+λ_p/2[2λ_p/λ_p] suffice to realize a hybrid decoder. Since [2λ_p/λ_p][2λ_p/λ_p]+1, it follows that the BRC-hybrid decoder uses at most 2λ_p[2λ_p/λ_p] NWs. This is within a factor of two of the information theoretic minimum.

FIG. 15 illustrates the second portion of a BRC hybrid decoder devoted to radial decoding. An arbitrary radial decoder in which NWs are labeled n, n+1, 2n, and 2n+1 is implemented on the two halves of the BRC axial code.

Examples of hybrid codes are now provided. Several combinations of axial and radial encodings that produce between 12 and 32 NW types while keeping small the number of shells and shell types are shown in FIG. 16. The reason for considering this small number of NW types is explained in the discussion of examples of radial codes.

In FIG. 16 there are shown parameters of hybrid codes that produce 12 to 32 different NW types (C, C_p). C_p is the number of BRC axial code types and λ_p is the number of NWs it uses. The shell distribution is shown for each radial code along with its number of NW types, C_p, the number of shells, n, shell types T_n, and MWs, λ_p, that it uses with a logarithmic decoder. The total number of NWs used with the λ_p-BRC decoder is λ_p=[1+2λ_p/λ_p]. The number of codewords in the code and the diameter of NWs are also shown.

A discussion is now made of the sensitivity of the BRC hybrid decoder to displacements. Note that if a fluidic process is used to assemble NWs with hybrid codes into parallel arrays, NWs will be displaced axially or lengthwise during assembly. To cope with this problem, as mentioned above, the axial code is repeated, as was done for purely axially-coded NWs.

If a BRC is shifted axially by the pitch of NWs, the doping pattern under NWs corresponds to that of another BRC (see Gojman et al., Decoiling of stochastically assembled nanoarrays. In Proc 2004 Int. Symp. on VLSI. Lafayette, La., Feb. 19-20, 2004). In other words, the set of BRCs is closed under displacements by multiples of a NW pitch. The same is true of hybrid codes.

Lemma: The set of hybrid codes when decoded using by a BRC decoder is closed under axial displacements of NWs by the pitch of a NW.

The analysis of the sensitivity of axial decoders to displacements by less than a NW pitch given here is the same as that briefly mentioned above in the discussion of the misalignment of axial codes, except that the NW pitch is larger for a given number of NW encodings. Since the probability of loss of control by NWs decreases with this parameter, hybrid codes are less sensitive to axial displacements than would be a comparably axial code. It is useful to repeat here the analysis.

Assume that the length of a doped region is the length of the region between two NWs that cannot be controlled by either NW plus 2W_{\text{overlap}}. Under this assumption NW doped regions are normal, the definition of which is given in above in the description of avoidance of on-type failures with axial codes.

As was mentioned above, the probability, P_{\text{control}} that a NW is controlled by a NW is P_{\text{control}}=\left(1-2W_{\text{overlap}}/W_{\text{pitch}}\right)^2.

A comparison is now made of various NW encoding strategies.

Radial, axial, and hybrid codes can be compared along various dimensions. Some of these are: a) the total area of a chip including the area of the crossbar as well as the area of a memory to translate external to internal addresses, b) the area of the crossbar alone under the assumption that the area of the translation memory can be ignored, c) the difficulty of manufacturing NWs with a given type of encoding, and d) the difficulty reliably assembling a memory. In light of uncertainties that exist with respect to these issues, one may compare NW encodings on the basis of the second measure, namely, the area of the crossbar alone. This is done by comparing the effective pitch of the NWs.

The effective pitch of NWs is their actual pitch increased by a factor that takes into account the loss of NWs due to duplication and/or misalignment. Note that misalignment is possible with both axial and hybrid codes.

It is preferred to compare only the effective pitch of radial and axial codes because the hybrid codes are generally inferior to axial codes. Hybrid codes incur almost the same misalignment penalty as axial codes but have increased pitch. Thus, in this comparison they are considered to be inferior to both radial and axial codes. However, hybrid codes may still be useful since a removable shell is always added to axially coded NWs to ensure that they remain separated during fluidic assembly, and this added shell may then be used to advantage.

To compare the effective pitch of NWs with axial and radial coding one may compute their raw diameter (see FIG. 17), which is also their raw pitch, under the assumption that each axially coded NW has one shell, as indicated above, and that the assembly process abuts one NW with another.

More particularly, FIG. 17 presents a comparison of axial and radial codes in terms of their effective NW pitch for four different values of C, the code size, for radial codes having s=2 or 3 shells and μ=4 or 5 different types of shell material. When decoded with a linear decoder, the radial codes have C=12, 20, 24 or 80 code types. The number of NWs with different addresses that occur with probability 0.99 among 1,000 NWs connected to 100 contact groups is shown. The value of P_{\text{control}}=\left(1-2W_{\text{overlap}}/W_{\text{pitch}}\right)^2 is computed when W_{\text{pitch}}=105 or 50 nm and W_{\text{overlap}}=5 or 10 nm, that is, when P_{\text{control}}=0.91, 0.81, 0.80 or 0.60. Results when P_{\text{control}}=0.81 are not shown.

Radially coded NWs will generally have more than one shell. One may then ask how many individually addressable NWs remain, after ignoring duplicates and misaligned NWs, when the NWs are organized into 100 contact groups (also known as "chomic regions") each of which contains 10 NWs. A Monte Carlo simulation was performed with four code sizes, namely, C=12, 20, 24 and 80, to determine how many addressable NWs are accessible among the 1,000 NWs in the 100 contact groups. These code sizes are those that are realizible with either two or three shells containing either four or five different types of material on radially coded NWs when linearly decoded (see FIG. 14). The simulations were performed under the assumption that either no misalignment occurs, or that it occurs with probabilities 0.09, 0.20 and 0.40. The three values where chosen because they are three of the values of 1-\text{P}_{\text{control}} that arise when W_{\text{pitch}}=105 or 50 nm and W_{\text{overlap}}=5 or 10 nm. The fourth case in which \text{P}_{\text{control}}=0.81 is ignored in FIG. 17 as it does not provide new information.

As these data indicate, radial codes have a slight disadvantage with regard to effective NW pitch. However, it appears that axial encodings are more difficult to prepare because of variation in the length of doped regions and the difficulty of producing abrupt transitions between differently doped regions. Also, axially doped NWs can be in an ambiguous conducting state. Finally, and because axially encoded NWs will require at least one shell to keep them separate under fluidic assembly, it can be advantageous to consider radially encoded NWs, especially if the number of differentially etchable shell materials can be increased beyond five.

Based on the foregoing discussion, it should be appreciated that radially encoded NWs provide an attractive method to differentiate NWs, such as when they are assembled into crossbars. The need for an effective method of differentiating NWs was made apparent in the discussion of the problems that arise with axially encoded NWs as a result of their random misalignment during the fluidic assembly of crossbars.

As a confirmation of the feasibility of radially encoded NWs, several examples of materials that are differentially etchable were provided, as were suitable etchants. Also discussed in detail were methods for decoding radially encoded NWs: the linear and logarithmic methods on one shell, and the \text{LinearLog} and \text{FullyLog} on multiple shells. It was demonstrated that a large number of NW types, C, can be created from a small number of shell materials, especially when decoded through the use of the linear method.

Algorithms were considered, for the various decoder types, for etching NWs to expose their insulated, lightly-doped cores to the fields applied by MWs. For each of these algorithms the number of etching steps was shown could be reduced to the sum of the number of material types in each shell, when etching is done in parallel. A consideration was also given to NW encodings that are a hybrid of axial and radial encodings.

Finally, a representative comparison of performance of the effective NW pitch for axial and radial encodings. This comparison suggests that axial codes may be at least slightly superior to radial codes, as measured by their effective pitch. However, given that axial codes require a more delicate manufacturing process, and that shells are useful for other purposes, it is apparent that radial codes in accordance with exemplary embodiments of this invention can function as an important type of NW encoding in the realization of devices, such as those that employ nanowire crossbars.

FIG. 19 illustrates a device 100 that contains a radially encoded nanowire array 110 that is constructed in accordance with the exemplary embodiments of this invention. The device 100 may be, or it may contain, a digital data storage memory and/or a PLA as two exemplary and non-limiting embodiments. Other circuitry may be contained in the device 100, for example a digital data processor (not shown) that operates in conjunction with a memory that is constructed using the radially encoded nanowire array 110. Electrical connections to the nanowire array 110 are made via chomic contacts (OCs) 115 that are electrically coupled to the various NWs 12, that in turn selectively turn off and on the radially encoded NWs 10, as has been explained in detail above.

FIG. 20 shows a data processor 130 that contains or is coupled to a memory 140 that stores a computer program
The execution of the CPP 150 by the data processor 130 is useful in fabricating the radially encoded nanowire array 110 in accordance with the exemplary embodiments of this invention. For example, the execution of the CPP 150 may be useful in assigning different shell materials to different shells and/or for planning and possibly controlling the selective shell material removal sequences discussed above for fabricating different ones of the decoders.

In general, some aspects of the various embodiments considered above may be implemented in hardware or special purpose circuits, software, logic, or any combination thereof. For example, some aspects may be implemented in hardware, while other aspects may be implemented in firmware or software which may be executed by a controller, microprocessor or other computing device, although the invention is not limited thereto. While various aspects of the invention may be illustrated and described as block diagrams, flow charts, or using some other pictorial representation, it is well understood that these blocks, apparatus, systems, techniques or methods described herein may be implemented in, as non-limiting examples, hardware, software, firmware, special purpose circuits or logic, general purpose hardware or controller or other computing devices, or some combination thereof.

Various modifications and adaptations may become apparent to those skilled in the relevant arts in view of the foregoing description, when read in conjunction with the accompanying drawings. However, any and all modifications of the teachings of this invention will still fall within the scope of the non-limiting embodiments of this invention.

As one example, it is within the scope of the exemplary embodiments of this invention to use at least one type of organic material as a shell material, either alone or in combination with one or more inorganic shell materials, such as those discussed above. In this case the selective shell removal process is one that is selected for preferentially removing the organic material. The use of optically-based polymerization/depolymerization processes are within the scope of the exemplary embodiments of this invention. It is also within the scope of the exemplary embodiments of this invention to use a wavelength selective chromophore in conjunction with a shell material to enable the selective removal process to be carried out using light having a chromophore-specific wavelength. As an example, a laser may be used to selectively remove or ablate certain shell material(s) and not others. Depending on the focal spot size of the laser, some number of NWs may be simultaneously treated in this manner.

In a still further non-limiting example a NW may be coated by simple absorption by water soluble polyelectrolyte such as polylysine. Then, in a masked structure, polylysine may be selectively removed using a neutral pH aqueous process that would not affect other shell material(s) such as oxide-based shell materials. This approach is compatible with existing photoresists, such as PMMA, that may be used to define regions wherein the selective shell removal process is desired to be carried out since PMMA is removed in an organic solvent that will not remove polylysine.

It should be appreciated that the selective removal of shell material from a NW can be carried out by any of a number of suitable techniques including, but not limited to, the use of wet or dry etching, the use of a solvent and the use of electromagnetic energy. These various shell material removal processes may be collectively referred to for convenience as "etching".

It should be appreciated that some shell materials may be best employed in conjunction with a dielectric material. For example, electrically conductive shell materials, such as Cu, when exposed may be coated with a suitable electrically insulating material, such as an oxide or a polymer as two non-limiting examples. It should be further appreciated that an array of nanowires constructed as described may be employed as a detector of molecules, such as biological molecules, by providing one or more molecule-specific receptors on one or more sets of NWs, where the presence of a specific molecule when bound to its receptor results in a detectable change in NW electrical properties.

It should be further appreciated that as employed herein an "array" of nanowires may be a one dimensional array, where the NWs run essentially in parallel to one another between ohmic contacts, or a two or three dimensional array, where two or more one dimensional arrays are arranged orthogonally (or with some other angular relationship) one to another. It should be noted that some of the features of the various non-limiting embodiments of this invention may be used to advantage without the corresponding use of other features. As such, the foregoing description should be considered as merely illustrative of the principles, teachings and exemplary embodiments of this invention, and not in limitation thereof.

What is claimed is:

1. A method to construct a device comprised of a plurality of nanowires (NWs) each comprised of a core and at least one shell, comprising:
   providing a plurality of radially encoded NWs where each shell is comprised of one of a plurality of different shell materials; and
   differentiating individual ones of the NWs from another by selectively removing or not removing shell material with areas to be electrically coupled to individual ones of a plurality of mesowires (MWs), where selectively removing or not removing comprises applying an etching process to the NWs using a plurality of etchants, where individual ones of the etchants are selected based on their ability to strongly etch one type of shell material but not strongly etch other types of shell material.

2. A method as in claim 1, wherein the plurality of etchants are sequentially applied.

3. A method as in claim 2, where a FullyLog decoder for n-shell NWs having $\alpha_1 (\alpha_2)$ materials in odd-(even-indexed) shells and $N=\alpha_1^{[n/2]} [\alpha_2^{[n/2]} [\alpha_3^{[n/2]}]]$ NW types is implemented with $M_{\text{FullyLog}} \sim 2^{[n/2]} [\log_2 \alpha_1] [\log_2 \alpha_2] [\log_2 \alpha_3]$ MWs, and $E \sim [n/2] [\alpha_1^{[n/2]} [\alpha_2^{[n/2]} [\alpha_3^{[n/2]}]]$ etching operations, where when $\alpha_1 < \alpha_2$ and $n$ is even, $N=(\alpha_1/\alpha_2)^n$, $M_{\text{FullyLog}} \sim 2^{[n/2]} [\log_2 N]$, and $E \sim \log(N).

4. A method as in claim 1, where selectively removing or not removing comprises etching the NWs within predetermined areas, and further comprising forming the NWs within the predetermined areas.

5. A method as in claim 1, wherein each core is surrounded by an insulating shell comprised of a dielectric material, the insulating shell being disposed between the core and at least one shell.

6. A method as in claim 1, where said shell materials comprise two or more of Cu, Al₂O₃, GaSb and InAs, and where said etchants comprise two or more of FeCl₃, NaOH, C₆H₄KNAO₂⁺HCl⁺H₂O₂⁺H₂O and C₆H₅O₂⁻H₂O₂.

7. A method as in claim 1, where two adjacent shells are comprised of two different shell materials.

8. A method as in claim 1, where each core is axially doped.

9. A method as in claim 1, where a linear NW decoder for $N=\alpha (\alpha-1)^{n-1}$ NW types containing $n$ shells of a types of shell materials is implemented with $\lambda_{\alpha} N$ NWs in M etching operations.
10. A method as in claim 1, where a logarithmic NW decoder for NWs with one shell and N-α types of shell material is implemented with 2 \( \log_2 N \) MWs and N etching operations.

11. A method as in claim 1, where \( \alpha = \lceil i/2 \rceil \) shell materials are divided into two disjoint sets of size \( \alpha_1 \) and \( \alpha_2 \), \( \alpha_1 + \alpha_2 = \alpha \), where the shell materials used to form the \( i \)th shell of each radial etching is chosen from the first set when \( i \) is odd, and from the second set when \( i \) is even, ensuring \( N = \alpha_1 \lceil n/2 \rceil \alpha_2 \lceil n/2 \rceil \) possible NW radial encodings.

12. A method as in claim 11, where \( \sigma_i \) denotes those shell materials that can appear in the \( i \)th shell, where \( \sigma_i \) depends on the parity of \( i \), where M is an arbitrary set of shell materials, where W represents a particular MW, and where, when no previous etching has been performed, [Etch(\( \sigma_{i+1} \), W), Etch(\( \sigma_{i+1} \), W), ..., Etch(\( \sigma_{i+1} \), W)] removes the outermost \( n \)-shell of every NW in a region under W, Etch(M, W) removes a shell from only NWs with a material in M in their \( i \)th shell, and [Etch(\( \sigma_{i+1} \), W), ..., Etch(\( \sigma_{i+1} \), W)] exposes the cores of the NWs.

13. A method as in claim 1, where a Linearlog decoder for \( n \)-shell NWs having \( \alpha_1 \) (\( \alpha_2 \)) materials in odd (even)-indexed shells and \( N = \alpha_1 \lceil n/2 \rceil \alpha_2 \lceil n/2 \rceil \) NW types is implemented with \( M_{\text{Linearlog}} = \lceil n/2 \rceil \alpha_1 + \lceil n/2 \rceil \alpha_2 \) MWs, and \( E = \lceil n/2 \rceil \alpha_1 + \lceil n/2 \rceil \alpha_2 \) etching operations, where when \( \alpha_1 = \alpha_2 = \alpha/2 \) and \( n \) is even, \( N = (\alpha/2)^2 \), \( M_{\text{Linearlog}} = \alpha n \), and \( E = \log_2 N \).

14. A method as in claim 1, where the etching process is a two-stage etching process, where when a nanowire that comprises the plurality of NWs is first etched, a resultant first decoder is used to discover which codewords are present at each oc inclusive contact (OC), and where if each OC has at least C codewords, regions under a second set of C NWs are etched to form a second decoder.

15. A method as in claim 14, where at each MW, at each OC, further comprising selecting an etching process that exposes one of C shell material sequence known to be present such that each of C NWs controls at least one particular NW at each OC.

16. A method as in claim 14, where \( S \) is a set of shell material sequences present at a particular OC, where there are \( C \) sequences in \( S \) such that each sequence contains a shell material type in some shell that no other sequence in \( S \) contains in that shell, and when this condition is met, C arbitrary codewords are deterministically assignable.

17. A method as in claim 1, where a size of a NW array space \( C_{\alpha} \) is in a range of about \( 2\sqrt{C_{\alpha}} \).

18. A method as in claim 1, where a size of a NW array space \( C_{\alpha} \) is in a range of about \( 10\sqrt{C_{\alpha}} \).

19. A method as in claim 1, where at least some of the plurality of NWs exhibit a hybrid encoding where the core is axially encoded and a plurality of shells are radially encoded.

20. A method as in claim 19, where a radial NW code is controlled by a radial decoder that uses \( \lambda_\alpha \) MWs and is used in conjunction with a \( \lambda_\alpha \)-BRD, and where a hybrid decoder is constructed by steps comprising:

   a) using \( \lambda_\alpha \) consecutive MWs for axial decoding, where under these MWs all shells are removed from all NWs such that these NWs function as an axial decoder, where the \( \lambda_\alpha \) consecutive MWs are used to select hybrid NWs with a given axial decoding by making non-conducting all NWs that do not exhibit a particular binary reflected codeword;

   b) using \( 2\lambda_\alpha \) MWs for radial decoding, where each NW contains a repeated binary reflected codeword such that if a pair of NWs are \( \lambda_\alpha \)/2-1 regions apart, exactly one lies over a lightly doped core region, and using \( \lambda_\alpha \) such pairs in \( [2\lambda_\alpha \lambda_\alpha] \) repetitions of the axial code to produce two identical radial decoders and applying the same etching operations to both NWs in a pair; and

   c) where one NW in each pair is adjacent to an exposed lightly doped core region, using the two radial decoders simultaneously to simulate a radial decoder, where the two \( \lambda_\alpha \) MWs select MWs with a given radial codeword, and where when a radial codeword and an axial codeword are selected simultaneously, only NWs with a particular hybrid codeword remain conducting.

21. A method as in claim 1, where the device comprises a digital data storage memory.

22. A method as in claim 1, where the device comprises a programmable logic array.

23. A method as in claim 1, where the shell material is comprised of a non-organic material.

24. A method as in claim 1, where the shell material is comprised of an organic material.