DNA Directed Construction of High Yield 2-D Nanowire Arrays

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This paper introduces a new idea for the construction of 2-D Nanowire arrays. This new method hopes to alleviate some of the current design issues encountered when constructing a 2-D nanowire array. Through the use of a DNA "curtain rod" nanowires can be arranged and then placed into arrays with much higher yield rates then current methods allowed.

As lithographic techniques reach their limit, new techniques must be devised to manufacture computation devices. One obvious approach involves "bottom up" assembly. Instead of using lithography to remove material to form the smallest features, miniature components of molecular dimensions are used to construct these features. Achieving the immense potential of such devices, however, entails obvious challenges—namely working with such microscopic components.

Semiconducting nanowires of a few nanometers in diameter have been successfully synthesized from a variety of materials. One fabrication method uses gold nanoballs as a catalyst, and the diameter of the nanoball defines the diameter of the nanowires. Wires with a 3 nm diameter and wires with lengths in the hundreds-of-microns range have been produced. The wires can also be doped both axially and longitudinally with precision. Flow techniques and the Langmuir Blodgett method have been successfully used to align the wires into parallel arrays on a desired substrate. Two such parallel arrays placed orthogonal to each other form a crossbar array, a useful architecture from which to construct a computing device. Engineering a crossbar array into a computing device, however, involves challenges like addressing individual nanowires and creating logic elements.

One current idea for fabricating Programmable Logic Arrays (PLA's) abandons manipulation of individual nanowires in favor of a stochastic approach. Batches of wires with unique doping patterns are grown. The number of batches—and therefore, types of wires—greatly exceeds the number of wires to be used in the array. After the batches are mixed, flow and Lamuirr-Blodgett procedures align the individual wires into parallel arrays, and the arrays are transferred to a substrate. A subsequent orthogonal layer forms a crossbar array. Standard micro scale lithographic wires provide support for the nanowires. The doping patterns in the overlapping wires allow Field Effect Transistor (FET) like effects, and thus a basis for memory and logic. Uniqueness of wires can be controlled to a desired probability based on the number of excess bases of wires. By one estimation, for example, if 10,000,000 types of wires are used, the probability that wires in a 1000 wire array will be unique is between .9-.95. Protocols have been formulated for discovery of the array architecture and mapping of logic onto the array.

While this stochastic method eliminates the challenge of manipulating individual nanowires, the approach imposes a set of limitations and inefficiencies into the fabrication process. The drawbacks stem from two major causes: inability to line up the ends of nanowires in the Lamuirr-Blodgett process and the inability to individually select

and place wires. A means to line up uniquely-selected nanowires might eliminate these limitations and provide a more efficient, robust nanowire-based computation device. We will propose such a method, but first expound upon the drawbacks of the former method.

Misalignment Effects

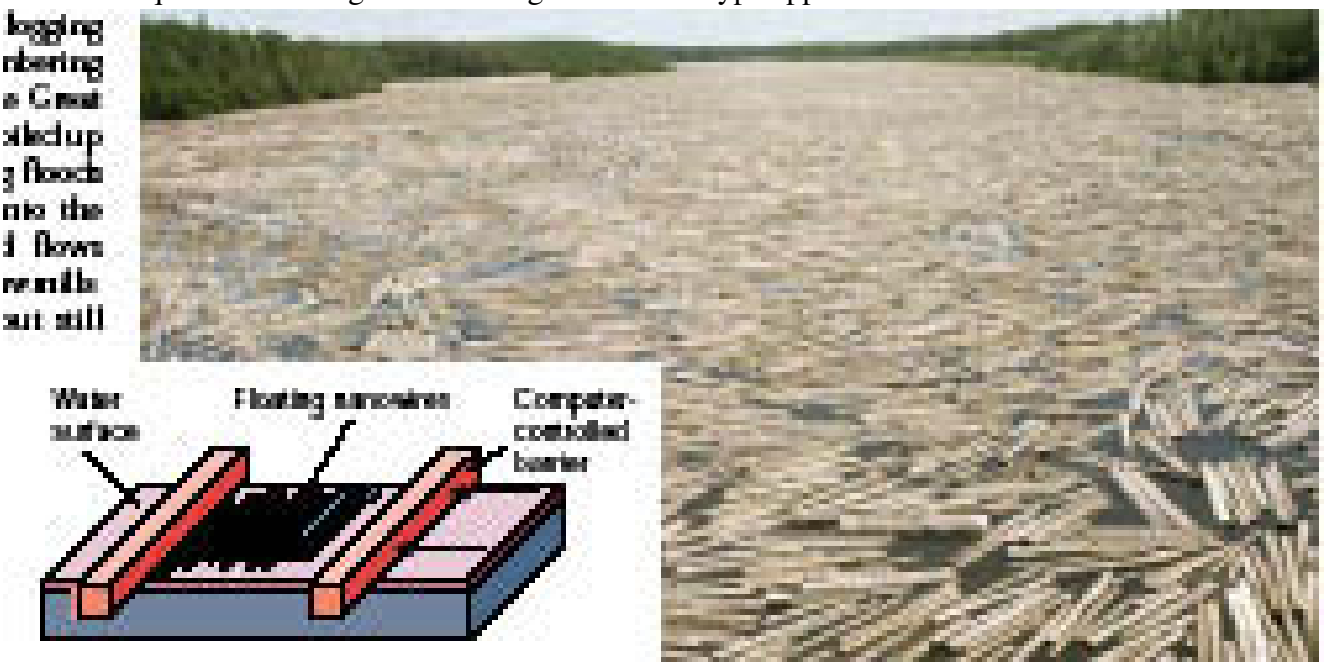
The aforementioned protocol utilizes Langmuir-Blodgett and flow techniques to align individual silicon nanowires. The space between the wires, or pitch, can be regulated by flow rate of the liquid or pressure applied to the sides of the wires. Although the wires are parallel, the ends fail to necessarily line up. This introduces a host of complications. When the wires are transferred to a substrate for use as computer architecture, the arrays are masked into a shape, e.g., a square. A certain proportion of wires will include a break because of the random distribution of wire ends and beginnings throughout the Langmuir-Blodgett surface. Thus, the proportion of usable wires is inversely related to the ratio of used wire length to total wire length. For example, if the length of an array is 1 micron and the total length of the wire is 5 microns, approximately 20% of the wires will be unusable. This effect can be minimized if the array dimensions are much smaller than the wire lengths, but as nanowire-based computation devices grow in size and complexity the required used-portion of the wire may become a greater portion of the overall length.

This nanowire PLA design relies on the doping pattern of the silicon nanowires to produce FET effects and thus computation. Current is controlled in the nanowires via microwires overlapping doped regions, and different doping patterns, or codes, allow for control of unique wires. Since the aforementioned method lacks alignment of the ends of the nanowires, the codes must be repeated the length of the wire in order to be position under the controlling microwires. Clever design of the codes solves some of the problems associated with differences in alignment of multiple bit pitches, e.g., using a “k-hot code” in which bit pitch alignment differences merely result in a rotation of the code. In some applications, like certain types of memory, a repeated code over the length of the wire would not impede operation. Other applications, however, like a PLA, would require development of new techniques to eliminate the effects of certain doped regions. One idea involves bulk doping the outside of the wire and then masking off the address regions—promising, but would require more steps and masking.

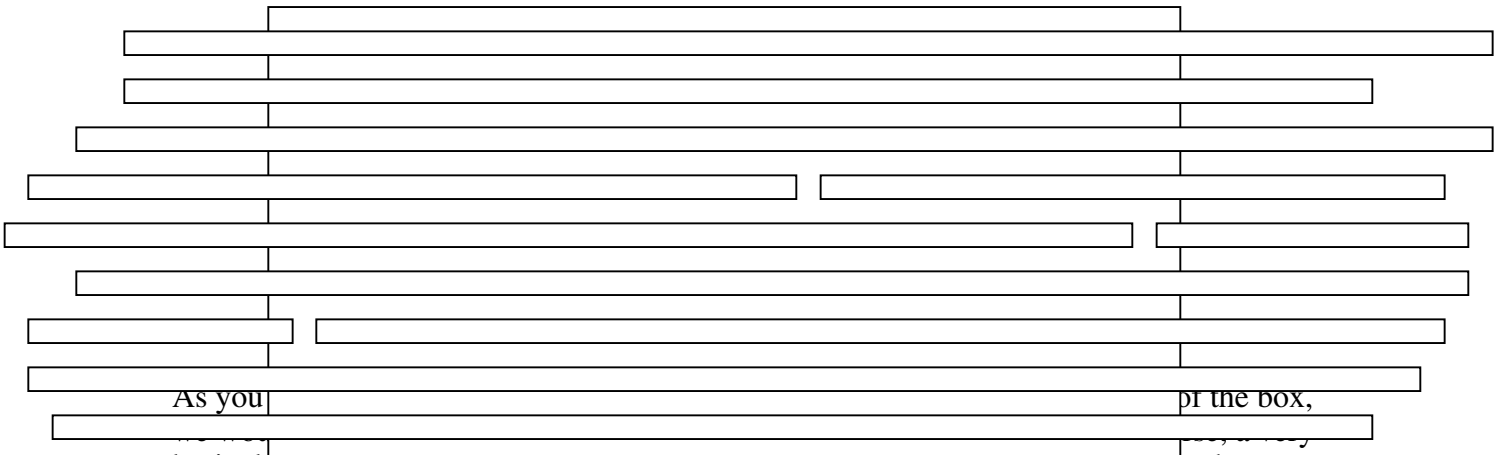
The size and well know properties of nanowires make them an excellent building block for molecular electronics. However, their very size makes them difficult to work with and so we need new strategies of assembly that will allow precise localization and interconnection. Using what we know and have learned at Computing Beyond Silicon Summer School about DNA and nanowires, we will present three possible plans for the use of DNA to align and even individually select the location of the individual nanowires on a sub-lithographic level. These methods are: a) the use of a DNA chip, b) using optical tweezers

Current popular methods of nanowire alignment include the flow method and the use of a Langmuir-Blodgett trough. There are, of course, others, but these are the two main ones that we learned about. The flow method is the use of a fluid flow to align the wires in a parallel manor. This method however does not allow for a fine adjustment of pitch. The

density of wires in the solution largely controls the pitch in this method. The Langmuir-Blodgett trough however has a much finer control over many aspects of the assembly. This technique can be thought of as a “logs on a river” type approach.



The logs are the nanowires and the bank of the river is the computer-controlled barrier. The nanowires are floated on the surface with the use a surfactant and pressure is applied to each side controlling the pitch. This is only good so far, however, before the wires begin to overlap. Also with this method, we cannot control the alignment of the wires in the trough. This means that in order to get a reasonable amount of wires that will not be broken, we must sacrifice large percentage of the length of the wires.



As you [illegible] of the box, basic drawing. In actuality, the percentage of wires lost is in direct proportion to the percentage of the box size to the wire size. A box that is half the size of the wires would cause a loss of near half of the connectivity all the wires. This method also means that any doping patterns that you have in the nanowires are randomly scattered throughout the array. This also creates a loss in connectivity when you attempt to integrate this array with your lithographic size input wires. The methods that we have developed are an

attempt to align the ends of each wire and even to select which wire goes where in the overall array. The advantages to this are obvious.

All three of our methods have several things in common which I will discuss now. The first is the nanowires themselves. We have selected silicon nanowires has our wire because the properties of silicon are very well know and they are often grown using a gold catalyst or seed. Gold in turn is very easy to bond to DNA using thiol groups and this is critical for our selection and aligning processes. Each wire will have a piece of single-strand DNA at the tip, which can be coded to align to a certain place in our "curtain-rod". The "curtain-rod" is made from DNA and will be what the tip of each rod bonds to and is thus aligned with all the other nanowires. We can wash the "curtain-rod" with a solution having only the nanowires with a specific DNA "tag" at one time, this allows us to better insure the binding of the nanowires in a specific location. The structure of the DNA used in our "curtain-rod" can vary depending on which of our three procedures is used. It is the creation of the "curtain-rod" which defines each of our three procedures.

The first of the methods we will discuss is the use of optical tweezers. In this method we attach a single strand of DNA to a glass bead on each end. Then using a pipette to hold one glass bead and optical tweezers to move the other, we can stretch our DNA into our "curtain-rod". With this method we can use either ssDNA or a hinge-segmented piece of DNA. After each hinge would be a "tag" or of ssDNA that would bond to a "tag" on our nanowires. If we used the ssDNA between the glass beads, then the "tags" on the nanowires would correspond to a specific location in the "curtain-rod". While this method might work well for experimentation of the bonding properties and of various DNA structures for our "curtain-rod", it would not scale up very well to any sort of mass production. I am sure that you are thinking of many modifications to this process, and believe me, so did we. This version of this method is merely the simplest we could think of and when you deal with a situation in which this method would be used, i.e. testing of bonding strength, "curtain-rod" strength and so on, the fewer the variables, the better.

Creating the DNA Curtain Rod

There are several methods that can be utilized in order to make a strand of DNA that can act as a scaffold for the nanowires. The first and least technical method is using a single strand of DNA with specific sites that can bind the complimentary strand of DNA that is attached to the nanowires via thiol linkages. To create a single strand of DNA that can bind 100 nanowires at a 10nm pitch, there needs to be approximately 2941 bases in the strand. One cannot create a ssDNA of this length utilizing synthetic methods currently available, but the problem can be circumvented by utilizing assembly PCR. In assembly PCR many short sequences of dsDNA are created and ligated together. The final piece of dsDNA is converted to ssDNA by taking only the forward primer and amplifying the Watson strand. In order to avoid strong secondary structure only certain base combinations will be used such as ATCC. This method can result in a very long strand of ssDNA that can be used as the curtain rod.

DNA tiles are another resource that can be used to make a DNA scaffold. DNA tiles can be made by creating DNA strands with Holliday junctions so that multiple strands of DNA are bound together (see Fig. 1). The tiles are connected to each other by creating tiles with sticky ends. Many tiles with a single-stranded overhang, where DNA-

functionalized nanowires can be attached to, can be joined together to create a DNA curtain rod with unique nanowire binding sites. To avoid contortions in the regions where sticky ends bind to each other, DAO-E tiles will be used (see Table 1 for explanation of nomenclature). In addition, a stretch of single stranded DNA can be used to seed the tiles and provide structural support.

A structure with a greater persistence length can be made by using DAE-E tiles to create a DNA tube as was done by Rothemund *et al*. The first row of tiles will be engineered to have single stranded overhang where the nanowires attach to. The rest of the tube will be made using tiles without the ssDNA overhang. Rothemund has shown that the persistence length of DNA tubes are about 4μm and can be formed with 4 to 9 tiles.

There are possible problems that may be encountered when building a DNA scaffold. For the ssDNA method, stability and synthesis are major factors for concern. A single-stranded piece of DNA of such lengths may not have the persistence length or strength to accommodate the large number of nanowires attached to it. The tile method may encounter stability problems similar to that of the ssDNA method. No studies have been done yet of how resilient the tiles are to external pressure, and it is possible that the sites where crossover occurs may not be stable enough to accommodate the length of the tile structures. Actual experiments must be done in order to determine which method is most effective.

Table 1

	1st letter	2nd letter	3rd letter	4th letter
DAO-E	Double crossover	Antiparallel sticky ends	Odd number of half-turns between intramolecular crossover	Even number of turns in the hybridization region
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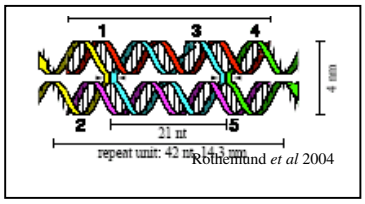
Figure 1: DNA DAE-E tile



DNA Chip

Another possible method of construction is to build the array on the lithographic plate its self. This would be done by using Dip-pen DNA placement. This works by utilizing and Atomic Force Microscope tip to place a strand of DNA directly onto the lithographic plate. (Figure 2) This process can be automated and has high resolution which will be useful if up-scaling of the technique is desired. The DNA will be placed in the corners of the plate and each corner will have a distinctly coded strand of DNA. These strands will act as anchors for the curtain rod DNA strand. The curtain rod when it binds to the corner strands will be stretched across the lithographic plate. Then the nanowires can be washed across the surface one type at a time. This allows for pre-selected wires of the desired length and quality to be placed along the curtain rod. As the nanowires are being washed down the surface of the plate they will be washed over the curtain rod and the nanowires with the DNA strand at the end will bind to the curtain rod creating the array. The flow will straighten the bound nanowire out and along the plate into proper position. (Figure 3) Once the first array is constructed the nanowires will be the process can be repeated orthogonaly to the first array to create the 2D array.

Figure 2

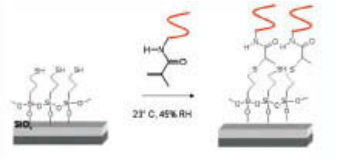
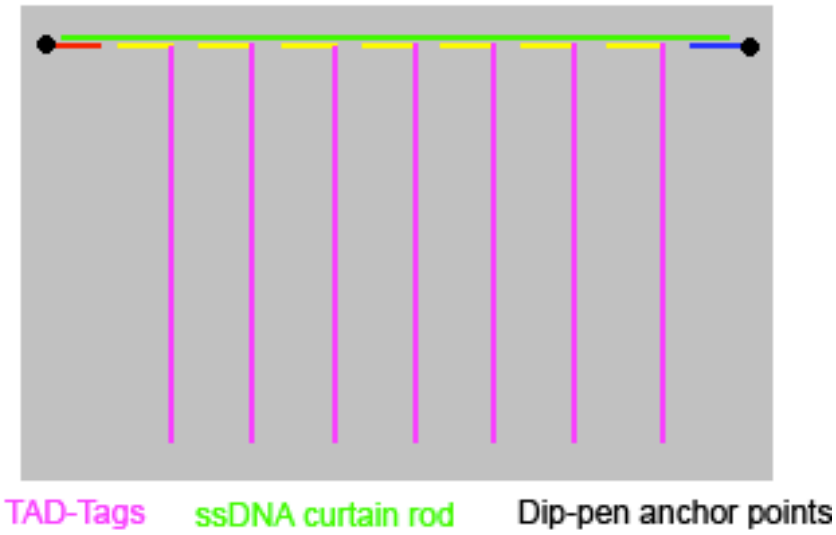


Figure 3



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