



## Hybrid Core-Shell/Modulation-Doped Nanowires and Decoding Methods

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### Field

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Nanowire differentiation is needed to control individual nanowires in crossbars, which are two orthogonal parallel sets of nanowires. Data in crossbars can be stored at the crosspoints formed by individual horizontal and vertical nanowires. The inventors describe axial and radial encodings and give efficient procedures to translate radial encodings into nanowire addresses. The inventors also describe hybrid axial/radial encodings. They show that such hybrid encodings greatly reduce the probability that nanowire control will be lost due to the random axial displacement that is a concomitant of the stochastic nature of nanocrossbar assembly.

### TECHNOLOGY

This invention is a new method for addressing nanowires (NWs) that uses core-shell NWs. This invention has several important advantages over that based on modulation-doped NWs. Modulation-doped NWs are semiconducting NWs in which some sections of lithographic length are lightly doped and some heavily doped. The inventors also examine hybrid core-shell and modulation-doped NWs. Core-shell NWs have the advantage that they are much less sensitive to random axial displacement than are modulation-doped NWs. They have the disadvantage that adding multiple shells increases their diameter and increases the spacing between NWs, thereby losing area efficiency. Hybrid encodings provide a compromise, providing the benefits of both encoding types.

To control modulation-doped NWs, insulated lithographic-scale wires (LWs) are placed at right angles to NWs so that electric fields may be applied without making contact with NWs. If a field of the appropriate size and polarity is applied to a lightly doped NW region, the NW becomes non-conducting, that is, the LWs and NWs act as field-effect transistors (FETs). This feature is the basis for the design of nanoarray-based PLAs and memories.

Also considered are core-shell NWs that have lightly doped semiconducting cores and shells made of differentially etchable material. The idea behind core-shell addressing is conveyed with a slightly inaccurate but simple description. Suppose that NWs have  $n$  shells and that each shell can contain  $T$  types of shell material. Thus, there are  $T^n$  different NW encodings. After NWs are placed in parallel on a chip,  $T^n$  regions of lithographic width are defined, one for each of the shell types in each shell. In the first lithographic region (LR) etching is done on all NWs in such a fashion that the cores of NWs are exposed that have the first shell material in the first shell but the cores of all other NWs are covered by at least one shell. This process is repeated in subsequent LRs for the successive shell types in the first shell and all  $T$  shell types in the  $n-1$  subsequent shells.

Insulated lithographic wires (LWs) are deposited over each LR. If a lightly doped core of a NW is exposed to a lithographic wire, it becomes non-conductive when an electric field of the appropriate intensity is applied to it. The NWs whose cores are not exposed are not subjected to an electric field sufficiently strong to

immobilize the majority carriers. If all but one of the first T LWs carries an electric field, exactly one of the Tn types of NW remains conductive.

Modulation-doped NWs have two problems that do not occur with core-shell NWs. First, because it is expected that NWs will be placed on chips using a fluid-based method, it is unlikely that their lightly doped regions will be perfectly aligned with the LWs. In fact, the alignment will be different for each NW, which means that the response of NWs to applied electric fields may be different. It is possible that for some NWs the change in conductance may be so low that all NWs with their doping pattern have to be disabled. This problem doesn't exist with core-shell NWs as long as the NWs make contact with ohmic regions at each end. (If contacts are not made, the NWs are inoperable, a problem that also occurs with modulation-doped NWs.) Second, modulation-doped NWs require a more precise manufacturing process than is believed necessary for core-shell NWs to make the transition between lightly and heavily doped regions sharp. A disadvantage of core-shell NWs is that their diameter will be large if a large number of shells is used, thereby negating the advantage of their inherently small features. As mentioned, hybrid encodings help cope with both disadvantages.

Hybrid core-shell/modulation doped NWs use both lightly and heavily doped regions on NW cores. This presents a control problem when core-shell encodings are added that is easily addressed. This invention addresses the problem of encoding data via shell sequences in core-shell NWs, the number of shells needed to provide a given number of addressable NWs, the number of LWs needed to address NWs based on the type of length of core sequences, as well as the manufacturability of a particular method of forming core sequences. It also addresses the combination of core-shell and modulation-doped NWs. In particular, this invention addresses the impact of such hybrid encodings on the probability that NWs are not controllable due to insufficient overlap between lightly doped NW regions and LWs.

INVENTOR(S):

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