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Self-Assembling Quantum Circuits with Clusters, Molecules and Quantum Dots

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1 Introduction

We have proposed a number of nanoelectronic architectures for collective computation, signal processing and Boolean logic [1-2]. All of these architectures can be realized with a uniform two dimensional array of quantum dots or metallic clusters (2-30 nm diameter) self-assembled on the surface of a double-barrier resonant tunneling diode and electrically linked by conducting conjugated molecular wires. These circuits can perform powerful computational and signal processing functions such as neuromorphic associative memory, image processing, Boolean logic and efficient solution of combinatorial optimization problems. The versatility of the architecture and the relative ease of synthesis make these entities - which we have termed "artificial quantum solids" - most attractive for quantum functional systems.

2 Quantum circuits

Quantum circuits have been an active area of research in the present decade [1-2]. Interest in this field stems from the popular notion that classical circuit paradigms would be inadequate for architectures of the next century. At the same time, advances in nanosynthesis based on self-assembly has opened up a new vista and opportunities for chemically "growing" circuits (as opposed to fabricating them piece by piece as in conventional lithography) abound. Our proposed architecture takes advantage of the merits of self-assembly and is extremely powerful and versatile. To our knowledge, this is the first proposal of its kind.

3 Basic architecture

The basic building block of our architectures is shown in Fig. 1. Each dot has a conductive coupling with its nearest neighbor established via molecular wires. The theoretical underpinnings and how this system can perform Boolean logic operations, associative memory functions, image processing and combinatorial optimization, have been described in numerous publications [1,2] and will not be repeated here. Instead, we will concentrate here on possible routes to synthesis.

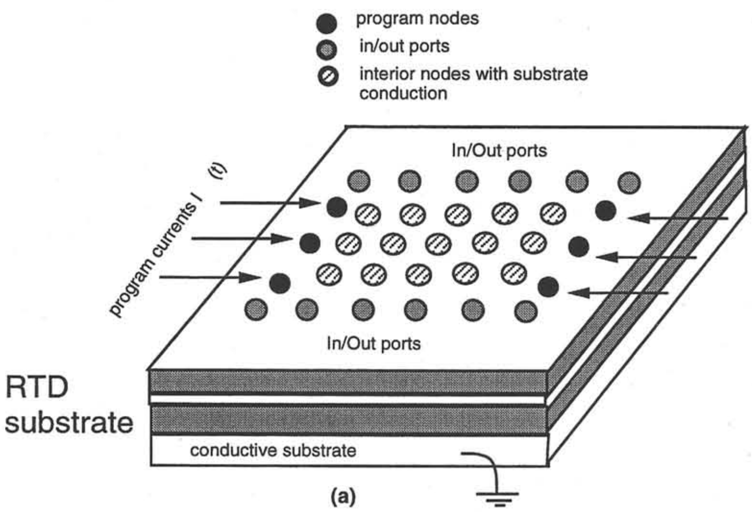
4 Self-assembly

The primary features of the basic system in Fig. 1 are 1) a uniform two dimensional array of nanometer-sized metallic islands with electrical connection between nearest neighbors, 2) low resistance coupling of the islands with the resonant tunneling structure underneath, and 3) a thin film resistive layer to provide bias connections to the islands.

Two dimensional arrays of metallic islands can be self-assembled on an arbitrary substrate in two different ways. A thin film of aluminum or gold can be evaporated on the substrate and electropolished under suitable conditions to produce the "egg-carton" pattern shown in Fig. 2 [3]. The troughs are removed by careful etching leaving behind the crests to form a periodic array of islands on the surface. These could be used as a natural mask to isolate mesas in the substrate underneath. The islands have a diameter of $\sim$ 30 nm with inter-island spacing of 150 nm. Adjacent islands can be linked with molecular wires bridged by gold clusters.

Another independent approach involves self assembling a two-dimensional close-packed array of 4-nm diameter gold clusters from colloidal suspensions of neutral encapsulated clusters [4]. A transmission electron micrograph of a gold cluster array is shown in Fig. 3. The intercluster electrical linking can be achieved by exposing the array to conjugated organic molecules (e.g. biphenyl-dithiol) with end-groups that bind to gold [4]. The measured in-plane conductance of linked cluster arrays, thus formed, exhibit strong single electron charging effects at room-temperature consistent with predicted resistances and capacitances of these wires [5, 6].

Low resistance coupling of the islands to the substrate underneath can be achieved if low-temperature grown GaAs (LTG:GaAs) is employed in the resonant tunnel-



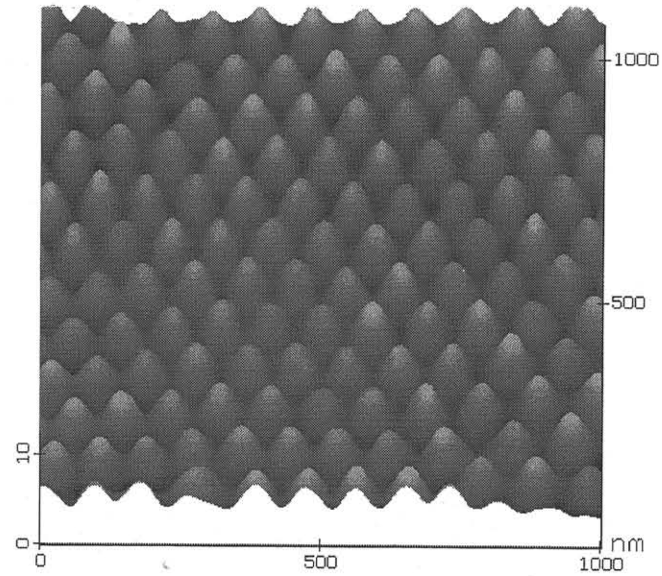


Figure 1: The basic nanoelectronic architecture consists of a uniform two-dimensional array of metallic islands self-assembled on the surface of a resonant tunneling diode structure. All input/output operations are performed on peripheral islands; this eliminates the need to access interior islands. A subset of the peripheral nodes are used to feed external current which provides a versatile programming capability for neural network functions. Not shown in this figure (for the sake of clarity) are the molecular wires which electrically link nearest-neighbor islands. The wires can have either ohmic or non-ohmic conduction characteristics.

Figure 2: Raw atomic force micrograph of the surface features in a thin aluminum film produced by electropolishing. This can be used to realize a two dimensional array of metallic islands of ~30 nm diameter.

ing structure. The islands can form ohmic contacts with LTG:GaAs without high temperature alloying [7] which could have caused size and shape distortion, diffusion on the surface, or chemical reaction of the molecules with the surface. LTG:GaAs is chemically stable and resists oxidation.

Finally, the thin film for bias connection is easiest to synthesize and is realized by growing a layer at low temperature in an MBE chamber [2].

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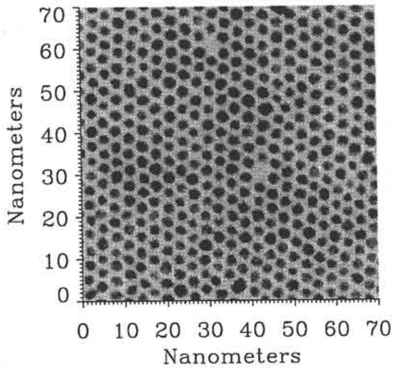

Figure 3: Transmission electron micrograph of a molecularly linked array of 4-nm diameter gold clusters.