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Feedback Process Control for Nano-manufacturing of Semiconductor Circuits

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Abstract: A feedback process control realizes 3-D circuits with a four nanometer footprint using a self-assembly nano-manufacturing facility including actuator controls. At this footprint level, quantum effects are significant. Our technology for quantizing the design of a digital circuit into a 3-D implementation using master equation models is based on a quantized Hamiltonian that is tracked by the physical Hamiltonian to deploy the circuit design. This quantum hybrid controller enables transformation of a desired circuit (expressed in logic and continuous rules) into manufacturing processes at quantum levels that includes interdependent multi-stage processes. The design procedure is interactive; it completely depends on the Hamiltonian of the circuit. It achieves performance criteria, such as maximize yield, maximize signal-to-noise ratio, and minimize entropy. The yield of the circuits is inversely proportional to the total entropy of the system. The Hamiltonian representation allows the computation of manufacturing parameters associated with this yield. Minimizing entropy produces high levels of yield.

Keywords: Self-assembly, Feedback control, Circuit optimization, Semi-conductor device fabrication, Scaffolding.

1. Introduction

A nano-manufacturing facility requires high levels of precision due to the strong quantum effects for devices at a 2 to 4 nanometer footprint. We develop a feedback process control to realize a 3-D scaffolding approach. Our technology uses master equation models that are based on a quantized Hamiltonian that is tracked by the Hamiltonian of a modified ink-jet based printer to deploy the circuit design.

We develop a quantum hybrid controller for manufacturing processes at the mesoscopic and quantum levels that includes interdependent multi-stage processes (e.g., quantum lithography, molecular epitaxial deposition, vertical dots, quantum well, quantum wires, etc.). The quantum hybrid controller is able to transform a desired circuit (expressed in logic and continuous rules) into manufacturing processes that will realize the nano-circuit and achieve performance criteria (such as maximize yield, maximize signal-to-noise ratio, minimize energy consumption, minimize dissipation, etc.).

The proposed system will include a language for the rules that describe the specifications of the circuit, an interface with the manufacturing processes to monitor and prescribe the sequencing, and a design dashboard. The quantum hybrid controller works with Hamiltonian operators to represent the system to achieve overall manufacturing synchronization and control. The quantum hybrid controller will enable automation of nano-manufacturing of nano-circuits. This will facilitate manufacturing of IoT systems.

An early version of this self-assembly procedure was published in [1]. Here we give more details of the design procedure. The manufacturing process that we consider is based on self-assembly and will be discussed in a future paper.

2. Technical Overview

This section summarizes our approach for the design and implementation of switching functions in a multi-tower realization of these functions using a quantum representation that allows the analysis and optimization of the design.

2.1. Scaffolding Implementation

Fig. 1 illustrates the contrast between standard semi-conductor manufacturing and the proposed scaffolding approach. In the scaffolding approach, a barrier layer may be added to an individual tower as opposed to a complete layer. Wires and tunneling bridges will be added, according to the specification from the quantum hybrid controller [2].

The quantum hybrid controller will enable automation of nano-manufacturing of nano-circuits. Once the "blueprint" for the desired circuit is encoded, the controller interacts with the manufacturing processes to achieve the desired behavior with desired performance metrics.

In a single tower, the crystal grows vertically surrounded by photoresist scaffolding. This design allows the use of different materials in towers and is more flexible than the standard approach. The photoresist creates a semi-permeable barrier; the closeness of the towers (less than 4 nm) allows circuit interaction through tunneling. The modeling of a tower creates boundary conditions that allow tunneling effects, as well as the addition of wires for interaction between towers. Fig. 2(a) illustrates a single circuit with photoresist scaffolding with crystal growth in a single vertical dimension. Fig. 2(b) illustrates circuit interaction between two circuits. The optimal control system includes scaffolding constraints to guide synchronization between towers by adding wires or tunneling bridges as needed.

The optimal control system implements the process control for manufacturing IoT systems represented by the switching functions. This manufacturing process control is based on a quantum representation of the switching functions [3]. These switching functions are implemented by quantum reversible circuits with a basic programmable unit. The difference between one quantum computational element and another is the program which is described by its realization functions.

Our approach for Hamiltonian construction is contrasted with a force balancing approach as in [4]. We uniquely quantize the Dirac Hamiltonian (Equation (11)) with Weyl quantization, as opposed to canonical quantization [5], because the quantum dynamic operation of the circuits is bounded (probability density operator dynamics has discrete spectrum).

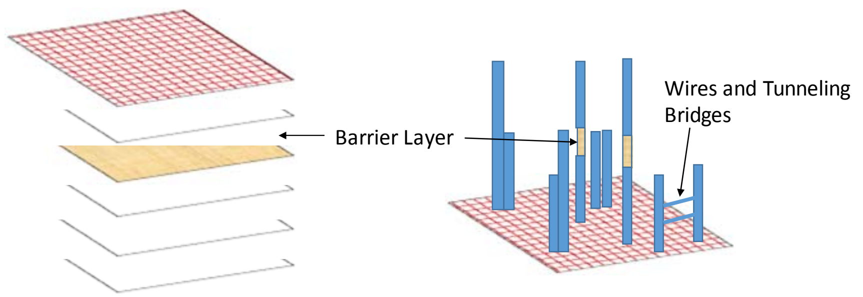

Fig. 1. Standard and scaffolding semiconductor circuits.

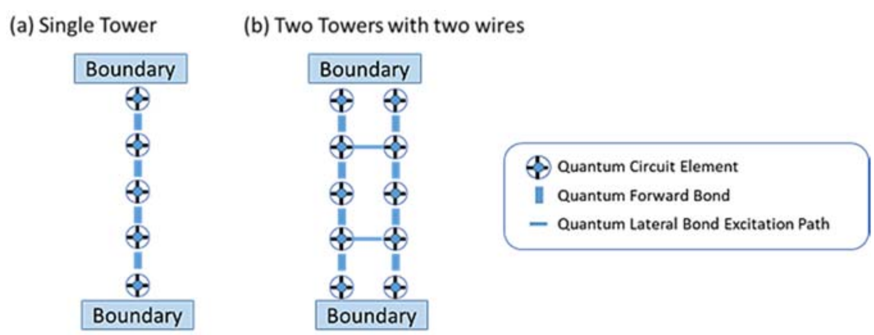

Fig. 2. Towers with photoresist scaffolding.

2.2. Quantum Hybrid Process Controller

The central approach in a quantum hybrid control is to express the switching functions of the design with a Hamiltonian representation. The switching functions and associated rules describing the desired behavior of the circuit will include: rules for physical principles, such as conservation of mass; rules that capture the tunneling effect and cross-talk; and soft rules for quantifying behavior and performance criteria. We construct the Hamiltonian from the switching functions and the rules using a Cooperative Distributed Inferencer (CDI) [6].

Fig. 3 illustrates the computational paradigm, composed of seven sequential steps. Each switching function, corresponding to a tower in the scaffolding, is either a map of the form

$$f: S_1 \times S_N \to D, \qquad (1)$$

where $S_i, i = 1, \dots, N$ and D are the finite subsets of the natural numbers expressed in binary encoding, or a solution of an iterative process (finite state machine) of the form

$$y_{n+1}^i = f^i(y_n^1, \dots, y_n^k), i = 1, \dots, k, \qquad (2)$$

where $f^i: S_i \to S$.

For both cases, we can express f by the encoding

$$\begin{aligned} &F:\left[0,1,\dots,p^{N-1}\right] \to \left[0,1,\dots,p\right] \text{ where } x = \sum_{s=0}^{N-1} n_s \bullet p^{N-1-s} \\ &\text{and } F(x) = \begin{cases} f(n_0,\dots,n_{N-1}) & \text{if defined} \\ 0 & \text{otherwise.} \end{cases} \end{aligned} \qquad (3)$$

The functions are application dependent, but they can always be expanded in terms of discrete orthogonal polynomials [7] and [8].

The **spectral continualization** step [9] consists primarily of completing the encoding of F with a step function Φ as

$$\begin{aligned} &\Phi: \left[0, p^{N-1}\right) \to \left[0, p^{N-1}\right) \text{ and} \\ &\Phi(y) = F(x), \text{ for each } y, y \in [x, x+1), x \in \left\{0, \dots, p^{N-1}\right\}. \end{aligned} \qquad (4)$$

With some needed modification, this continualization process can be extended to discrete functions that are specified as solutions of iterations of the form

$$Z_{k+1} = g(Z_k, k) \text{ with } Z_k \in S^N, S = \{0, \dots, N \mid N \text{ finite}\} \qquad (5)$$

for each k, where k is an integer.

Modifying the methods of Kushner and Clark [10], the encoding and continualization of a process leads to a differential equation of the form

$$\dot{x}(t) = G(x(t), t) + B(t) \qquad (6)$$

with a sampling rule of the form

$$G(\bullet, t) = \text{continualized version of } g(\bullet, k), \qquad (7)$$

where $t \in [k\Delta, (k+1)\Delta), k \in N$, and $B(t)$ is an error correction term to account for the finite approximation of the continuous model.

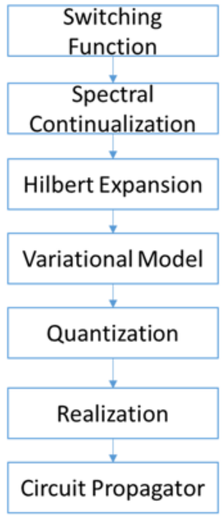

Fig. 3. Design procedure.

The **Hilbert expansion** consists of selecting a basis of discrete polynomials to express the function Φ in the Hilbert space via an orthogonal expansion,

$$\Phi(y) = \sum_{y \in [0,p]^N} \beta_k \bullet \phi^k(y) \qquad (8)$$

$$\beta_k = \left(\int_0^{p^N} \Phi(x) \bullet \bar{\phi}^k(x)\, dx \right) \Big/ \left(\int_0^{p^N} \phi^k(x) \bullet \bar{\phi}^k(x)\, dx \right) \qquad (9)$$

This quantum hybrid *controller* is distributed to match the scaffolding implementation. The specific architecture will be discussed in the section on scaffolding architecture. In this architecture, each vertical device (e.g., tower) in the circuit corresponds to an agent.

The **variational model** is constructed by an inverse algorithm that generates the Lagrangian of the IoT system, as detailed in [10]. The action integral defined by the Lagrangian L, generates the same trajectories as in (6). We convert the problem to a variational problem because the associated Lagrangian, and corresponding Hamiltonian, encodes the switching functions of the IoT we want to realize. Specifically, the variational problem is defined as

$$\begin{aligned} &\min_x \int L(x, \dot{x}, t)\, dt \text{ where } L \text{ is generated by} \\ &\text{the following linear hyperbolic equation} \\ &q_t + G_x q + \dot{x} q_x + (\dot{x} G_x + G_t + B_t) q_{\dot{x}} = 0 \\ &\text{and } q(x, \dot{x}, t) = L_{\dot{x}\dot{x}}(x, \dot{x}, t). \end{aligned} \qquad (10)$$

Equation (10) can be solved analytically by the method of characteristics and a quadrature integration [11]. However, we have to add constraints due to the scaffolding that add boundary conditions. In addition to the dynamics associated with the Lagrangian in (10), we add constraints according to Dirac [11]. The classic Hamiltonian of the circuit is

$$H'(x,p) = H_0 + \Omega Q^{-1}\{\Omega, H_0\} + H_f\,, \tag{11}$$

where H_0 is the model of the physics of the circuits, Ω is the model of the scaffolding constraints, Q is the matrix of the circuit interactions between nearby scaffolds, and H_f is the Hamiltonian associated with the switching function to be computed [12].

The **quantization** of the Lagrangian is carried out by converting the Lagrangian to a Hamiltonian function [5]. Specifically, $p = L_{\dot{x}}$ is the generalized momentum of the system. The canonical commutation relations $[x_k, p_l] = i\delta_{k,l}$ are satisfied for $k, l = 1, \dots, N$. The Hamiltonian is

$$H(x,p) = \sum p_k \bullet \dot{x}_k - L, \ \text{Legendre transformation} \tag{12}$$

The quantization of (12) is carried out by constructing $\hat{H}\left(\hat{x}, \frac{1}{i}\frac{\partial}{\partial x}\right)$ by replacing x with $\hat{x}$, and p with $\frac{1}{i}\frac{\partial}{\partial x}$ in $H(x,p)$.

The evolution equation of the IoT system is completely specified by the corresponding Schrodinger equation,

$$i\hbar\frac{\partial}{\partial t} = \hat{H}\left(\hat{x}, \frac{1}{i}\frac{\partial}{\partial x}\right) \tag{13}$$

The Hamiltonian as defined in (12) is a model of how the circuits in the design will operate in the quantum domain. It must satisfy the condition

$$\left|\hat{H} - H_0 + H_f\right| \le \varepsilon\,, \tag{14}$$

where H_0 is the model of the physics of the circuits, and H_f is the Hamiltonian associated with the switching function to be computed [13].

The realization step is to construct H_f so that the discrete spectrum of the total Hamiltonian $H_0 + H_f$ has to satisfy

$$\left(H_0 + H_f\right)\left|\Psi_k\right\rangle = \lambda_k\left|\Psi_k\right\rangle\ , \tag{15}$$

where $\{\lambda_k, k = 1, \dots, N\}$ is the set of eigenvalues of $H_0 + H_f$ with corresponding eigenvectors $\{\Psi_k, k = 1, \dots, N\}$.

The central realization step is to deploy H_f that satisfies

$$\begin{gathered}\left|\lambda_k - \beta_k\right| \le \varepsilon / N \text{ and} \\ \int_0^\infty \left|\phi^k(x) - \Psi_k(x)\right| dx \le \varepsilon\end{gathered} \tag{16}$$

Note that, by the continualization process of the switching function, the computational problem has been reduced to computing functions with scalar arguments that approximate the desired switching function, as in (16).

The circuit propagator based on the design criterion in (16) is a self-assembly quantum implementation of the transition between the discrete states of the spectrum. Each level in Fig. 4 corresponds to a frequency of a component in the circuit.

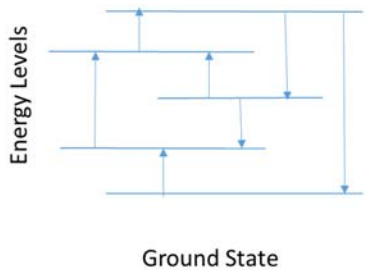

Fig. 4. State transitions between eigenvectors. Up arrows are field driven; down arrows are spontaneous.

Our direct self-assembly is implemented by guiding the assembly with the propagation of spectral transitions of the Hamiltonian, as opposed to other approaches that use force to propagate the self-assembly [4, 14].

This transition is realized in a scaffolding implementation where the components of each scaffolding step have a representation illustrated in Fig. 5 and Fig. 6. In Fig. 5, each column of computational elements corresponds to a tower in Fig. 1.

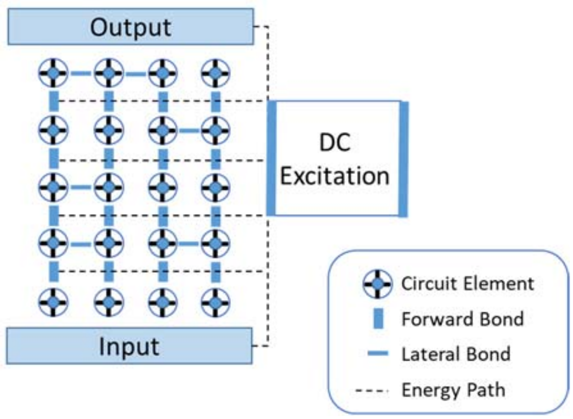

Fig. 5. Quantum processor.

The transitions illustrated in Fig. 6 are described by the following equations, as in [15]. The probability density operator is defined by

$$\rho(t) = \sum_j p_j \left|\Psi_j(t)\right\rangle\left\langle\Psi_j(t)\right| \tag{17}$$

and by differentiating (17) and using some algebraic manipulations with (13), we get the master equation for propagating ρ,

$$i\hbar\frac{\partial}{\partial t}\rho=\left[\hat{H},\rho\right]=\hat{H}\rho-\rho\hat{H}. \tag{18}$$

The probability transition in Fig. 6 realizes the master equation associated with the Hamiltonian. The device in Fig. 6 is deployed in the crystal by self-assembly [16].

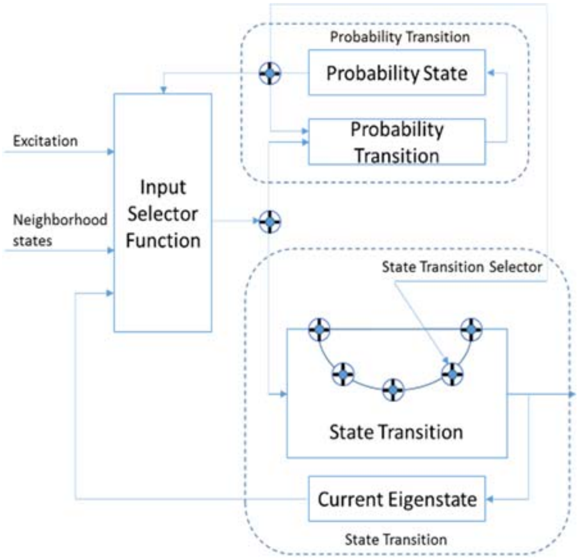

Fig. 6. Generic Circuit Element.

3. Nano Self-assembly

Our technique for self-assembly is based on our scaffolding architecture. The circuits are built almost independently of each other; they only interact with each other via bridges which are either energy transfer bridges or information transfer bridges. Each of our circuits is an almost reversible quantum circuit [3]. Each circuit is a quantum cascade of common elements, as illustrated in Fig. 2 and Fig. 6. Fig. 2 shows the cascade, and Fig. 6 shows a generic circuit.

As the assembly propagates, the Hamiltonian describing the circuit is locally modified to configure the generic element with high Quality Factor (QF) in the current step. When the Hamiltonian describing the circuit becomes the identity, the circuit is complete. In Section 4, the hybrid architecture combining the design with the implementation of the circuit is described. This self-assembly is similar to the force balance approach in [4]. The design computation and implementation has elements of the concepts behind directed self-assembly of block co-polymers, as in [17].

4. Design Architecture

The overall design architecture is shown in Fig. 7. For a given implementation, each tower in Fig. 1 realizes a specific switching function. The coupling of the switching functions is realized by a "bridge", as in Fig. 5. For manufacturing purposes, each tower is self-assembled by a "control agent" as shown in Fig. 7.

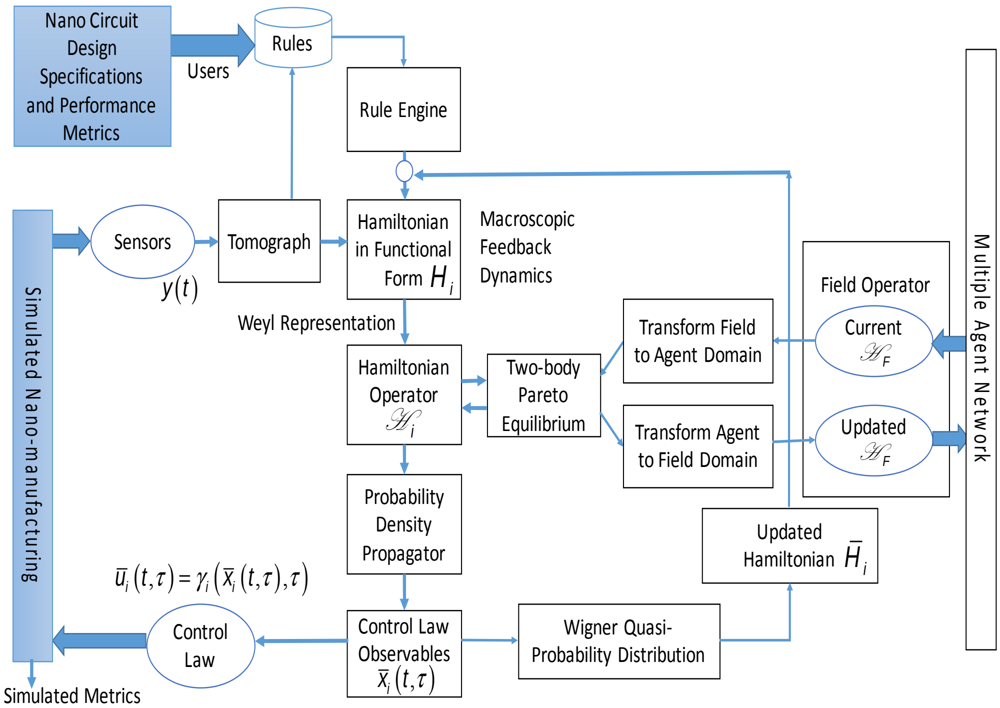

Fig. 7. Quantum hybrid controller for agent *i* representing a tower in the nano-circuit.

The control law specifies how to propagate the Hamiltonian to achieve the desired behavior and performance. Fig. 7 illustrates the system for an agent. The synchronization between the towers on each layer is achieved by updating the agent Hamiltonians with a Hamiltonian field that represents the overall circuit and performance characteristics. This synchronization will determine when to construct a quantum wire, for example, that achieves sharing of energy. Instead of computing all combinations of agents (which is impossible, due to the impossibility of solving an *n*-body Pareto game), we play a two-body Pareto game between each agent and the design field to update both the agent Hamiltonian and the design field Hamiltonian representing the complete circuit [18]. Since each agent contributes to the design field Hamiltonian, and is, in turn, updated by the design field Hamiltonian representing all of the agents, the agents are synchronized to achieve the overall objectives.

The sensor data provides the current state of the system, such as the current layer that is being processed and other information relating to the performance criteria. Our tomograph engine collects measurements as the "nano-manufacturing printing" occurs and converts this into potential representations that update the Hamiltonian of the circuit in construction.

This tomograph data is in the form of polynomial approximations representing potential forms of the Hamiltonian in construction. The sensory data driving the tomograph engine are sequences of images generated by an electron microscope. While a spatial resolution of one nanometer is achievable with the tomograph approach, this aspect still needs a significant amount of experimentation and research.

The control variables in the quantum hybrid controller specify the devices (e.g., vertical dots, quantum wells, quantum wires, etc.) in each layer that comprise each tower, and the sequencing of the processes as each layer is constructed. The control law prescribes how each layer is constructed and is derived from the propagation of the Hamiltonian.

We propose to develop a computationally efficient algorithm for accurate and robust image processing based on a method called Speeded Up Robust Features, or SURF, for short. SURF is a local feature descriptor based on the sum of Haar wavelets around points of interest that are detected using an integer approximation of the determinant of the Hessian operator.

5. Manufacturing Processes

The manufacturing process is directed self-assembly. Each circuit implements a Hamiltonian that encodes its functionality. The Hamiltonian of each circuit tracks a model Hamiltonian computed by each agent quantum hybrid controller. We use a meta-material lens [19-20] to parallelize the construction of multiple devices simultaneously. The lens is designed with meta-materials that allows the distribution of the control Hamiltonian for circuits in the parallel self-assembly [1]. The integration of the quantum hybrid process controller with parallel devices is illustrated in Fig. 8. The number of parallel devices under construction depends on the quality and density of prismatic components of the meta-material lens.

6. Conclusions

This paper overviews a technology for the design and implementation of programmable tower semiconductors. The design technique is based on continualizing a spectral representation of switching functions [10] and [11].

Two of the authors (Kohn and Nerode) are using this technique for building photo-magnetic antennas in silicon crystals. This design requires separability offered by vertical scaffolding to partially isolate the circuits until interaction is required. This application will be published in the next few months.

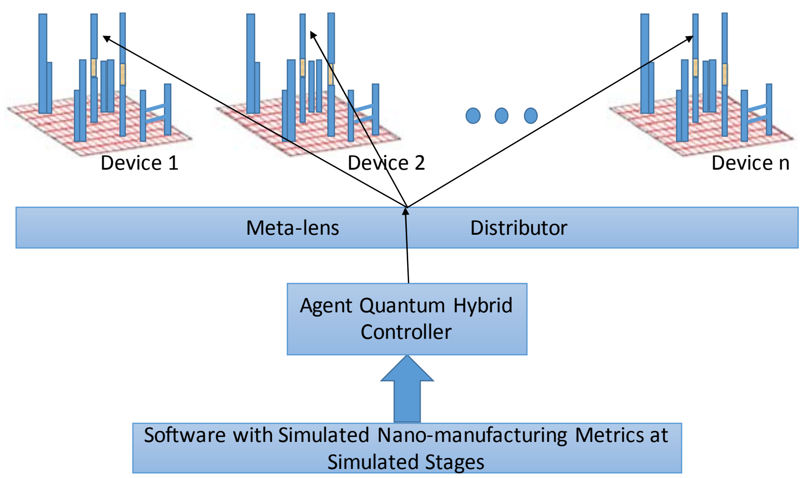

Fig. 8. Parallel self-assembly schema for devices using a quantum hybrid controller for each circuit.

A future paper will give details of yield and complexity. The quantum representation is essential because the quantum effects at 4 nanometer footprint are dominant. The two-layer device (probability and state transitions in Fig. 6) represents the generic structure of each component in a tower and a bridge. Experimental work in that direction is being pursued at the present time.

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