A Technology Aware Magnetic QCA NCL-HDL Architecture

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***Abstract*—Magnetic Quantum Dot Cellular Automata (MQCA) have been recently proposed as an attractive implementation of QCA as a possible CMOS technology substitute. Marking a difference with respect to previous contributions, in this work we show that it is possible to develop and describe complex MQCA computational blocks strongly linking technology and having in mind a feasible realization. Thus, we propose a practicable clock structure for MQCA baptised "snake-clock", we stick to this while developing a system level Hardware Description Language (HDL) based description of an architectural block, and we suggest a delay insensitive Null Convention Logic^{TM} (NCL, [1]) implementation for the magnetic case so that the "layout=timing" problem can be solved. Furthermore we include in our model aspects critically related to technology and real production, that is timing, power and layout, and we present the preliminary steps of our experiments, the results of which will be included in the architecture description.**

I. Introduction and motivation

QCA, in their general meaning, are bistable cells coupled through electromagnetic forces. In the micro-magnetic implementation, single-domain nanometer pills-shaped magnets exhibit two stable magnetic states, "up" and "down", carrying thus a binary information thanks to their reciprocal influence based on a "domino" effect. Many works have been proposed in recent years either on circuits and architectures (see for all [2]) or on detailed physical nanomagnets behavior analysis (see for an example [3]). In the former case it is shown that, should technology be of support, computation would be feasible, and many of the traditional CMOS based digital implementations could be adopted. In the latter case, experiments are carried on to demonstrate the feasibility of the idea adopting to date production phases. Anyway, the two aspects are seldom integrated, thus the design approach is splitted in two averted points of view, while, as we have experienced especially in the recent CMOS technology success story, the strength of a design methodology is based on the ability of linking them as much as possible. We believe thus that, at the light of the current scientific MQCA scenario MQCA, the time is mature for entangling circuit design with technology when the aim is demonstrating the feasibility of the MQCA computation paradigm.

In this work we show our approach for twisting computation and implementation. The idea is to assess a practicable and not theoretical technological implementation for MQCA; to constraint the circuit design to such a base, to solve at the architectural level the critical limitations due to it; to describe the circuit behavior so that implementation details can be taken into account, thus circuit performance can be estimated and feedbacks to technologists suggested; to step progressively to the physical implementation and to enrich the circuit description with on the field data.
In this paper we show the preliminary results of such approach. In section II the foundamental technological hypotesys is explained. In section III an example of circuit description is given with a specific architectural solution adopted and with the "low-level" details added to it. In section IV the preliminary technological implementation and performance analysis are described.

II. A feasible three phases clock

It has been demonstrated (see [4]) that for MQCA as well as for molecular QCA, an adiabatic switching is suggested to assure a correct information propagation. This means that switching of a nanomagnet from state "up" to state "down" is favoured if an intermediate state is reached first. That is, an external filed is applied so that the pill "memory" (previous magnetization state to "up" or "down") is erased, and, at this point, as soon the external field is released, an input can more easily and with lower power loss, force the new "up" or "down" to the pill. This is particularly important when the input of nanomagnet-B is another nanomanet-A, which can force on the coupled nanomagnet-B only a limited magnetic field due to its intrinsic characteristics (shape and material).

Such external field is meant as a clock, as it is iteratively switched on and off and allows the evaluation phase, even though it has not the "traditional" function of a clock signal. One of the related aspects is the clock organization in complex computational structures. In this work, thus, we propose, starting from [5], a solution to clock distribution, "snake-clock", which we judge more feasible for the multiple-phases clock distribution, necessary to allow the information propagation without losses in complex nanomagnets arrays. First, phases are three, differently from the four ones introduced for the molecular case: in figure 1.a the RESET, SWITCH and HOLD sequence is shown both in time and space. In figure 1.b the behaviour of nanomagnets grouped (each clock phase should serve a group of pills for the unavoidable size difference between the pills and the line generating such a phase) in the correspondent clock zones is depicted: when a cell group is in the HOLD phase the stable “up” and “down” states own the digital information; thus they can force it toward the near group which is in the SWITCH state, that is, its previous state has been previously “cancelled” thanks to a reset, and now they are ready to be influenced. The group in the following region is itself in the RESET state. In figure 1.c the top view

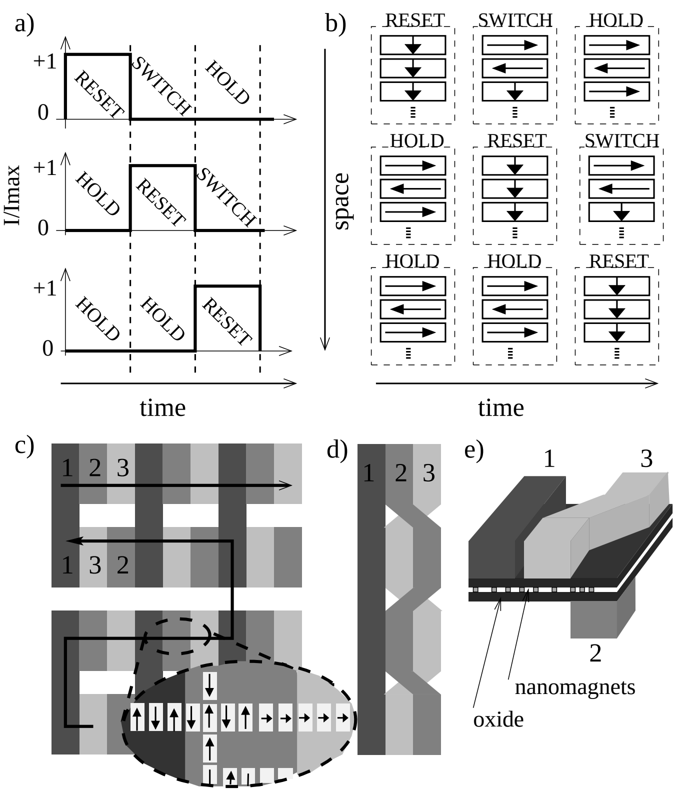

Fig. 1. Proposed clock organisation: a) Threes phases sequence, b) MQCA behaviour in three zones, c) Snake clock logic zones view, d) Snake clock layout top view e) Snake clock physical distribution

of the clock zones is sketched together with the information flow: this style still allows the information flow in both the horizontal and vertical directions, but, as the correct phase sequence (1,2,3 in figure) must be assured, only a “snake” like propagation is possible. Even if this seems a limitation, it is feasible with current technology, differently from previously proposed solutions. This is also evident in the layout and physical views 1.d and 1.e respectively. The nanomagnets arrays can be sandwiched between two thin oxide layers, and on the top and bottom of this structure metal wires carrying the clock signal can be routed. One stripe (phase 1) can be straight, while the others (phases 2 and 3) should be routed in a zig-zig style, interlaced as they were twisted but belonging to two different metal layers. Active nanomagnet pills cannot be present in zones where metal wires are oblique.

III. SNAKE-CLOCK NCL-HDL MQCA DESCRIPTION

The proposed structure influences the circuit model we describe. We use VHDL, as proposed in [6] for general QCA, to model the circuit behaviour, but we also adapt the description specifically to the magnetic implementation and to the “snake-clock” related information propagation. An example is in figure 2 detail on the right, where registers are associated to phase transitions (each register is indeed placed on a different phase zone), and combinational gates (in this case a Majority Voter, that is the basic QCA component) to the “computational” part of a clock zone (in this example for space reason phase three only has a computational block). Wires and blocks are composed of arrays and structures of nanomagnets as in the “arrow” example in figure 1.c detail.

One of the most critical problem in QCA is the “layout=timing” one, that is the overall timing and correct behaviour of QCA is dependent on the circuit layout. As an example, inputs to the Majority Voter (MV) should change synchronously to assure a correct computation. This can be easily assured in simple circuits by equalizing the number of magnets carrying the three signals to the MV so that no skew is sensed. But in complex circuits this could be impossible to assure. In [7] NCL is proposed as a possible solution. Here we adapt it to the magnetic and snake-clock case with our HDL representation and build a meaningful circuit to show that these three aspects can be well combined. The chosen circuit here is a counter, which allows to test both the combinational and the sequential aspects of the NCL synthesis, and, as shown in figure 2, which is asynchronous. The information propagates from one NCL block to the next only when “acknowledged”, thus, even if a delay occurs as the layout is such that the number of magnets carrying signal F0 and F1 (inputs to the circuit on the left) is different, the computation is correct. More in detail, the information is not a sequence of data, but, as visible in the simulation bottom line, is an alternative sequence of data (D) and null state (N). This is possible as each logic signal is coded using two bits so that for each couple a 0-0 is a null state, while a 1-0 or 0-1 is meant as a data state (logic 1 or logic 0 respectively). State 1-1 is not admitted. The N-D-N sequence assures that before a new data is evaluated, both inputs must go to 0, independently on their delay. This solves the layout=timing problem. NCL blocks are registers (not the phase transition registers which are related to the snake-clock organization and used in the HDL description) and combinational (an example of the simplest, the TH22 is in the right detail, already adapted to the magnetic-snake-clock organization). In the counter example, three registers are needed as this is a 3-bit counter, while the combinational gates assure the correct counter evolution (they represent the future state network of this simple finite state machine). At the block level point of view, the NCL organization implies that an acknowledge is needed for an input evaluation to occur; this is supported by the A_{IN} and A_{OUT} control signal included in each register and assures that only when each block has data ready the next stage is allowed to evaluate them.

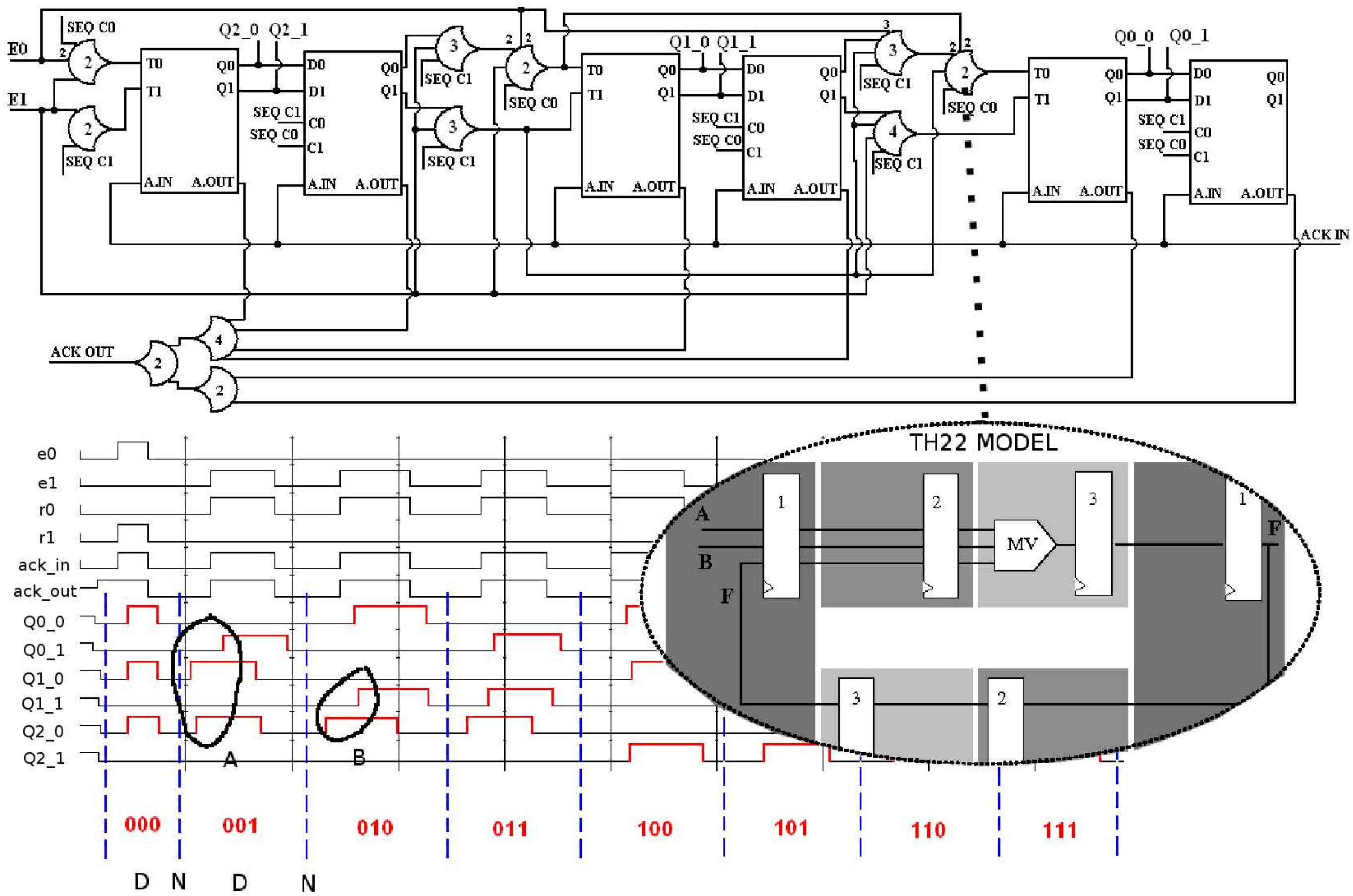

Fig. 2. NCL counter architecture, simulation (delay effects in the left details) and port NCL-TH22 model for the snake clock implementation (right detail).

The simulation waveforms in figure 2 show how the counting sequence is correct, even if the entire structure is organized on phases correspondent to the the snake clock and the basic cells are reorganized and based on the MV block. Thus a full magnetic and snake-clock NCL structure has been demonstrated here and assures promising potentialities for further architectures developments, as it solves a critical limitation of MQCA and is also based on a practicable clock structure.

The description has been also enriched with other physical related information as *delay* (see A and B details on the simulation waveforms in figure 2), *power* dissipation based on values in [9] and using a VHDL-AMS description (a detail of power variation during counting is in figure 3), and *layout* as a dependency on the number of magnets necessary to carry a signal from a gate to the other is inserted in the model (detail in figure 3 right).

We plan to further improve these descriptions related to the physical implementation as we believe that not only the architecture is more physically meaningful and variations to it can be decided on a technology basis, but also feedbacks to technology can be generated, so that it can be evolved towards a usable solution.

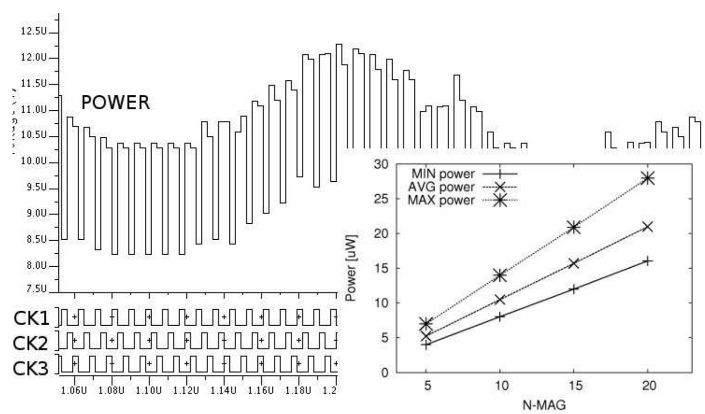

Fig. 3. Power simulation for the NCL counter; detail: power dependency on the number of magnets due to layout.

This is the reason why we are setting up our own experiments, still at the preliminary phase at present time and driven by results partially presented in literature (e.g. [**?**]), with the aim of jointly proof the feasibility of architectures and specifying meaningful objectives to physical experiments.

IV. Preliminary experiments

MQCA arrays have been produced using RF magnetron sputtering and Electron Beam Lithography (EBL). The arrays feature a square-lattice arrangement of single elliptical cylinders, composed by a soft ferromagnetic material (face centered cubic cobalt). Such arrays are realized over an electrically conductive layer (either gold or copper) deposited on an adhesion promoter (titanium) over a stiff substrate (100 silicon wafer). The electrically conductive layer plays an important role both in extracting the secondary electrons generated during the EBL exposure and in controlling the magnetization by the dc-current-induced Oersted field. The samples that so far have been tested consist of 30-nm-thick Co MQCAs featuring various aspect ratios, ranging from 1:2 up to 1:5, with a major axis ranging from 2.5 down to 1 μm (see figure 4), to be reduced in the near future. The aspect ratio induces different shape magnetic anisotropies and is used either to facilitate or to hinder the magnetic switching. The magnetic configuration associated to the logic state has been characterised by field-assisted Magnetic Force Microscopy (MFM) imaging. The magnetic field acting on the MQCAs was produced either by an electrical current flowing in the metallic substrate or by two Helmholtz coils.

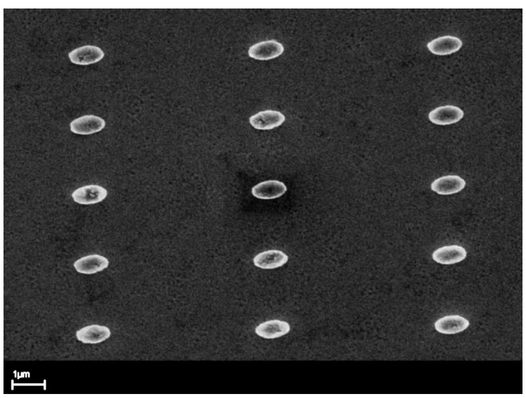

Fig. 4. FESEM picture of a Co MQCA array precursor; thickness: 30 nm; major axis: 1 μm; minor axis: 500 nm; spacing: 5 μm along major axis, 2 μm along minor axis.

In our most recent analysis however we demonstrated a tip-induced magnetization reversal, with an effect dependent on the relative orientation of the fast scan axis with respect to the ellipses major axis. We developed a numerical algorithm in order to increase the signal to noise ratio of the MFM data matrices and to let information connected with the magnetic status of each elliptical pillar emerge, starting from a registering routine described elsewhere [10] and implementing a new differential approach that allows to completely exclude the effects of a tip magnetization reversal occurred during the submission of an external magnetic field. This means that a difference in the MFM maps taken with different values of magnetic field may be correctly addressed either to the sample or to the tip.

The image shown in figure 5 is a collection of differential frames of a single MQCA element taken with a fast scan axis orthogonal with respect to the major axis (a, 90^o) and parallel to it (b, 0^o), with an external magnetic field of -100 Oe (left elements) and $+100$ Oe (right elements), after registering the images and subtracting the zero field reference state. The magnetization alignment with respect to the ellipse axes is defined by the grey scale contrast anisotropy: the (a) elements feature a white spot respectively at bottom and on top of the pillar, while the (b) elements feature a white line running respectively on the right and on the left borders. This contrast corresponds to a magnetization lying along the major axis (a) and along the minor one (b). The switching was obtained by the application of an external magnetic field and strongly influenced by the acquisition configuration.

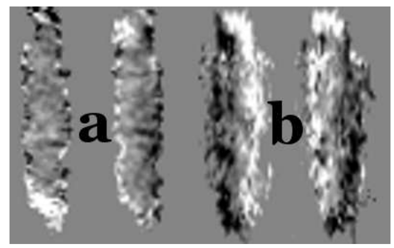

Fig. 5. Registered differential MFM frames of a single MQCA pillar; from left to right: 90^o and -100 Oe external field, 90^o and $+100$ Oe, 0^o and -100 Oe, 0^o and $+100$ Oe.

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