DIGITAL NANOMAGNETIC LOGIC

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As CMOS matures, there is interest in exploring alternative paradigms for implementing digital circuits. A number of researchers are considering the benefits of incorporating ferromagnetic materials into electronic devices for both memory and logic applications. The features of ferromagnetic materials which make them potentially attractive are: in-built non-volatility, which makes them well suited to mobile and low power applications; a highly non-linear response, which can be accurately controlled, making them potentially suited to implementing logic functions; good prospects for future scaling to nanometre sizes.

While the benefits of ferromagnetic materials are clear, what is less well understood is what type of devices should be made. Magnetic Random Access Memory (MRAM) offers one paradigm for information storage, where Boolean states are represented by the magnetisation direction of a sub-micron magnetic element, and is read back using a magneto-resistive effect [1]. A second paradigm can be found in recently proposed reconfigurable logic schemes, where the ferromagnetic element is used to select an electronic logic function or electronic signal routing [2]. In this talk, I describe two other potential paradigms.

The first is magnetic cellular automata, which is a room temperature implementation of the well-known Notre Dame quantum cellular automata scheme [3]. Cellular automata systems use a network of dots, which share information with their nearest neighbours. A careful selection of the interaction rules between neighbours can allow information to be propagated and processed within the network of dots. We have demonstrated experimentally and at room temperature how a chain of 110nm diameter dots made from a soft ferromagnetic material ($Ni_{80}Fe_{20}$) can communicate by short-range magnetostatic interactions, and how this can be used to pass information from one end of a chain of dots to the other [4]. See Fig. 1. In principle, logic gates can also be made in this way. Magnetic cellular automata scheme suffer from two major drawbacks. The first is the relatively low energy of the information-carrying magnetic soliton, making the system susceptible to thermally activated errors. The second is the stringent fabrication requirements: the 110nm dots were separated by just 25nm.

The second scheme that I will discuss is derived from the magnetic cellular automata, but is thermally robust and does not require very high resolution lithography in its fabrication. Called domain wall logic, the scheme represents information by the magnetisation direction within a sub-micron track of ferromagnetic material [5]. The interface between logic states (rising or falling edges) is mediated by a magnetic domain wall, which can be swept through an interconnected network of nanoscale magnetic tracks by an applied magnetic field or even by an electronic current. To date, we have demonstrated magnetic interconnects for domain walls, logical NOT gates, interconnect cross-over structures and 1:2 fan-out structures. An AND gate is currently under investigation. We have used these circuit elements to construct a number of all-magnetic logic circuits. These include a simple synchronous ring oscillator (Fig. 2), an 11-bit serial shift register (Fig. 3) and a frequency divider circuit (Fig. 4). We have demonstrated experimentally that domain wall propagation speeds as high as 1500 ms^{-1} are possible [6]. While not competitive with the best CMOS speeds, this does nevertheless mean that devices could operate at 100MHz, which would be suitable for a number of niche applications such as smart-cards and smart-tags and other low-cost low-performance applications. The very simple device structure may also be a suitable candidate for realising 3-dimensional logic networks on a chip.

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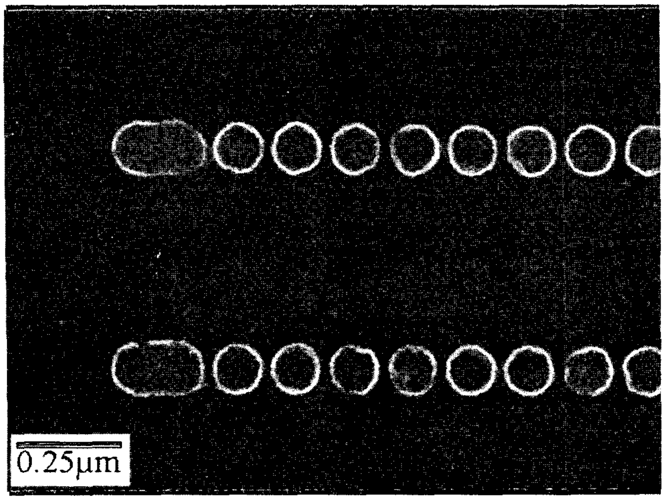

Fig. 1: A chain of magnetic dots 110nm in diameter. Information is passed from one dot to the next by magnetostatic interactions.

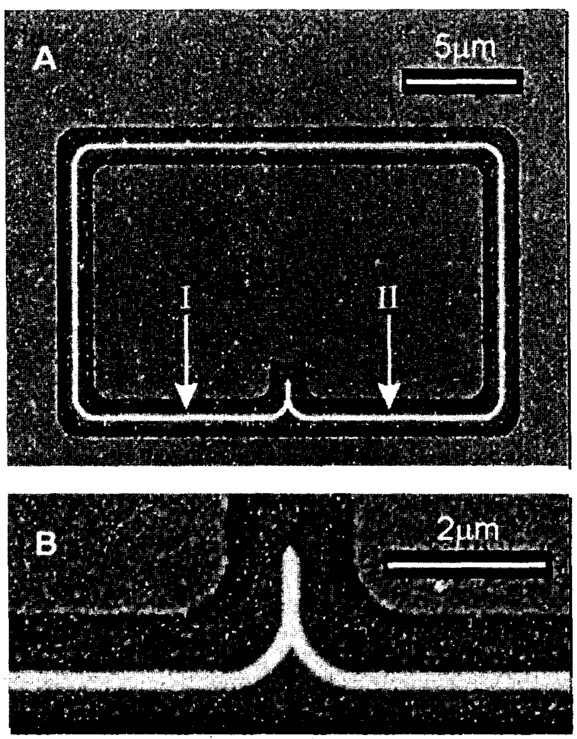

Fig. 2: A nanomagnetic NOT gate incorporated into a feedback loop to form a simple synchronous ring oscillator. Panel A shows the complete circuit and panel B shows an enlargement of the NOT gate itself.

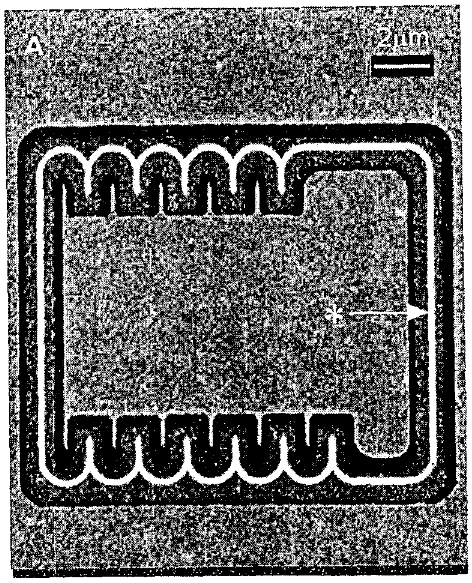

Fig. 3: 11 NOT-gates connected in a ring to form an 11-bit serial shift register.

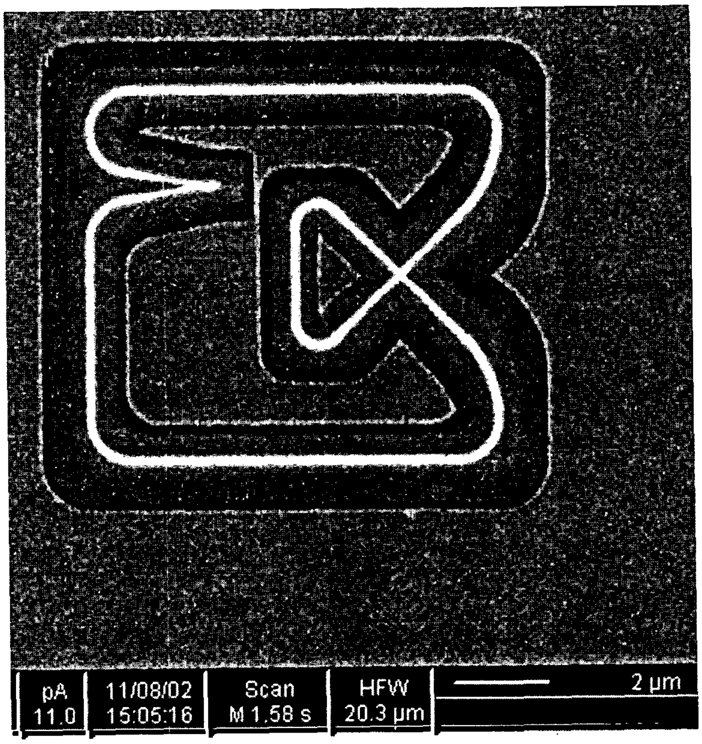

Fig. 4: A NOT-gate combined with a cross-over element to make a digital frequency divider. The circuit divides the frequency of an applied magnetic field by 5.