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Integrated Nanomagnetic Logic System in Perpendicular Magnetic Media

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Abstract

As CMOS scaling will face fundamental limits, more and more attraction is dedicated to beyond CMOS technologies. A very promising candidate in this scope is Nanomagnetic Logic (NML), which exploits the interaction of field-coupled nanomagnets to perform logic operations and benefits from inherent memory functionality. NML is especially suited for ultra-low power applications and supplementary features complex digital majority votes, room temperature operation and high integration density. In this work NML in magnetic media with strong perpendicular magnetic anisotropy is favored over in-plane NML, because it provides shape flexibility of the single magnets and switching field modification by well-defined local ion beam irradiation. The purpose of this work is the demonstration of an operating NML system, the investigation of reconfigurable NML and the integration of NML in state-of-the-art CMOS circuits.

Etched islands of Co/Pt multilayer media represent the magnets, which feature single-domain behavior. Their magnetization direction in easy-axis defines the boolean logic state. Locally confined ion beam irradiation generates weakest links in the magnets, which govern the magnetic reversal process. Irradiation on the edge of the magnets originates asymmetric coupling to neighboring magnets and thereby implements directed signal flow. The development of NML systems, composed of Co/Pt magnets, is supported by calibrated micromagnetic simulations. New methods and setups for an enhanced metrology, e.g. an arbitrary magnetic field module integrated in a conventional MFM setup, enable the analysis of the quality of the magnetic media and the investigation of NML devices and systems.

An exemplary NML circuit is realized by a line of antiferromagnetically coupled magnets, acting like a magnetic inverter chain. A magnetic power clock is theoretically conceived and applied to drive the NML circuit. Antiferromagnetic ordering is propagated experimentally in the chain, verifying information propagation. A circular magnetic inverter chain is deployed to demonstrate the transport of arbitrary magnetic information. For the first time an NML circuit in perpendicular magnetic media is operated successfully over hundreds of clocking cycles. The invention and implementation of a programmable, nonvolatile magnetic input extends the NML technology and paves the way towards runtime reconfigurable NML systems. Furthermore, electrical interfaces are developed to integrate NML in the back-end of common CMOS circuits and provide a hybrid technology with symbiotic characteristics. An Oersted switching input interface and an extraordinary Hall-effect read-out sensor are presented as interfaces, that connect the electronic and magnetic domain. The resulting embedded programmable Nanomagnetic Logic technology combines logic and memory functionality and thereby potentially leads towards a new era of information processing.

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