TRANSISTOR-FREE LOGIC GATE AND CHIP DEVELOPMENT IN ARTIFICIAL 2D HONEYCOMB MAGNETIC MATERIAL

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application No. 63/553,475, filed February 14, 2024, which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH & DEVELOPMENT

[0002] This invention was made with government support under DE-SC0014461 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

FIELD

[0003] The field of the invention relates generally to transistor free logic gates, and more specifically to using 2D honeycomb magnetic material to generate transistor-free logic gates.

BACKGROUND

[0004] Current electronics and computers are built upon transistor technology. The transistors are used to build logic gates that allow the electronics and computers to operate and perform logical operations. The transistors are configured to operate as logical gates, such as, AND gates, OR gate, XOR gates, and NOT gates. On issue with current transistors is size. When it comes to electronics, the drive is to get a small as possible. This allows designers to improve the computing power of the electronics without increasing the size. However, currently used transistor technology is based upon silicon. This material leads to limitation in the minimum size that can be used. Furthermore, there are significant power dissipation issues that arise from tightly packed silicon based transistors. Accordingly, there is a need to determine other techniques for making logical gates.

[0005] This background section is intended to introduce the reader to various aspects of art that may be related to various aspects of the present disclosure, which are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the present disclosure. Accordingly, it should be understood that these statements are to be read in this light, and not as admissions of prior art.

BRIEF DESCRIPTION

[0006] In one aspect, a magnetic artificial honeycomb lattice is provided. The magnetic artificial honeycomb lattice includes a multiplicity of connecting elements separated by hexagonal cylindrical pores. The (a) hexagonal cylindrical pores (i) have widths that are substantially uniform; and (ii) are substantially equispaced. The (b) connecting elements includes a magnetic material layer. The connecting elements have: (i) lengths that are substantially uniform; (ii) widths that are substantially uniform; and (iii) a thickness of the magnetic material layer that is substantially uniform and an average thickness. The magnetic artificial honeycomb lattice is configured to receive two input currents and configured to output an output voltage based upon the two input currents. The magnetic artificial honeycomb lattice may have additional, less, or alternate functionalities, including those discussed elsewhere herein.

[0007] In another aspect, a method of making a making a magnetic artificial honeycomb lattice is provided. The method includes depositing a layer of magnetic material on a substrate. The substrate comprises an artificial honeycomb lattice topography. The artificial lattice topography includes a multiplicity of connecting elements separated by hexagonal cylindrical pores. The (a) hexagonal cylindrical pores (i) have widths that are substantially uniform and (ii) are substantially equispaced. The (b) connecting elements includes a magnetic material layer. The connecting elements have (i) lengths that are substantially uniform; (ii) widths that are substantially uniform; and (iii) a thickness of the magnetic material layer that is substantially uniform and an average thickness. The (c) magnetic artificial honeycomb lattice is configured to receive two input currents and configured to output an output voltage based upon the two input currents. The method may have additional, less, or alternate functionalities, including those discussed elsewhere herein.

[0008] Various refinements exist of the features noted in relation to the above-mentioned aspects. Further features may also be incorporated in the above-mentioned aspects as well. These refinements and additional features may exist individually or in any combination. For instance, various features discussed below in relation to any of the illustrated embodiments may be incorporated into any of the above-described aspects, alone or in any combination.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The Figures described below depict various aspects of the systems and methods disclosed. It should be understood that each Figure depicts an embodiment of a particular aspect of the disclosed systems and methods, and that each of the Figures is intended to accord with a possible embodiment thereof. Further, wherever possible, the following description refers to the reference numerals included in the following Figures, in which features depicted in multiple Figures are designated with consistent reference numerals. There are shown in the drawings arrangements presently discussed, it being understood, however, that the present embodiments are not limited to the precise arrangements.

[0010] Figure 1A shows an example honeycomb lattice vertex in accordance with at least one embodiment.

[0011] Figure 1B illustrates magnetic charges at the vertexes of the artificial honeycomb lattice shown in Figure 1A.

[0012] Figures 2A-2D illustrate the four potential magnetic charges in the honeycomb lattice, shown in Figure 1A.

[0013] Figure 3 illustrates a system for using the honeycomb lattice shown in Figure 1 as a logic gate.

[0014] Figure 4 illustrates a system for using multiple honeycomb lattices shown in Figure 1 to build an algebraic logic unit.

[0015] Corresponding reference characters indicate corresponding parts throughout the drawings.

DETAILED DESCRIPTION

[0016] The field of the invention relates generally to transistor free logic gates, and more specifically to using 2D honeycomb magnetic material to generate transistor-free logic gates.

[0017] Spin ice is a magnetic substance that does not have a single minimal-energy state. It has magnetic moments (*i.e.*, "spin") as elementary degrees of freedom which are subject to frustrated interactions. By their nature, these interactions prevent the moments from exhibiting a periodic pattern in their orientation down to a temperature much below the energy scale set by the said interactions. Spin ices show low-temperature properties, residual entropy in particular, closely related to those of common crystalline water ice. The most prominent compounds with such properties are dysprosium titanate ($Dy_2Ti_2O_7$) and holmium titanate ($Ho_2Ti_2O_7$). The orientation of the magnetic moments in spin ice resembles the positional organization of hydrogen atoms (more accurately, ionized hydrogen, or protons) in conventional water ice.

[0018] Spin ices are materials that consist of regular corner-linked tetrahedra of magnetic ions, each of which has a non-zero magnetic moment, often abridged to "spin", which must satisfy in their low-energy state a "two-in, two-out" rule on each tetrahedron making the crystalline structure. This is highly analogous to the two-near, two far rule in water ice. While the ice rule leads to an extensive entropy in water ice, so does the two-in, two-out rule in the spin ice systems – these exhibit the same residual entropy properties as water ice. Be that as it may, depending on the specific spin ice material, it is generally much easier to create large single crystals of spin ice materials than water ice crystals. Additionally, the ease to induce interaction of the magnetic moments with an external magnetic field or electrical current in a spin ice system makes the spin ices more suitable than water ice for exploring how the residual entropy can be affected by external influences.

[0019] Spin ice materials are characterized by a random disorder in the orientation of the moment of the magnetic ions, even when the material is at very low temperatures. Alternating current (AC) magnetic susceptibility measurements find evidence for a dynamic freezing of the magnetic moments as the temperature is lowered somewhat below the temperature at which the specific heat displays a maximum. The broad maximum

in the heat capacity does not correspond to a phase transition. Rather, the temperature at which the maximum occurs, about 1 K in $Dy_2Ti_2O_7$, signals a rapid change in the number of tetrahedra where the two-in, two-out rule is violated. Tetrahedra where the rule is violated are sites where the aforementioned monopoles reside.

[0020] Spin ices are geometrically frustrated magnetic systems. While frustration is usually associated with triangular or tetrahedral arrangements of magnetic moments coupled via antiferromagnetic exchange interactions, spin ices are frustrated ferromagnets. It is the very strong local magnetic anisotropy from the crystal field forcing the magnetic moments to point either in or out of a tetrahedron that renders ferromagnetic interactions frustrated in spin ices. Most importantly, it is the long-range magnetostatic dipole–dipole interaction, and not the nearest-neighbor exchange, which causes the frustration and the consequential two-in, two-out rule that leads to the spin ice phenomenology.

[0021] For a tetrahedron in a two-in, two-out state, the magnetization field is divergent-free; there is as much "magnetization intensity" entering a tetrahedron as there is leaving. In such a divergent-free situation, there exists no source or sink for the field. According to Gauss' theorem (also known as Ostrogradsky's theorem), a nonzero divergence of a field is caused, and can be characterized, by a real number called "charge". In the context of spin ice, such charges characterizing the violation of the two-in, two-out magnetic moment orientation rule are the aforementioned monopoles. The effective charge of a magnetic monopole is Q in both dysprosium and holmium titanate spin ice compounds. These compounds may be applied in a nanoscopic artificial 2D honeycomb lattice, also known as a Kagome lattice.

[0022] Figures 1A, 1B, and 2A-2D are schematic depictions of spin configurations on a two dimensional honeycomb lattice vertex. Figure 1A shows an example honeycomb lattice vertex in accordance with at least one embodiment. Figure 1B illustrates magnetic charges at the vertexes of the artificial honeycomb lattice shown in Figure 1A. Theoretical research suggests that at sufficiently low temperature arrange themselves to create a spin solid state manifested by the periodic arrangement of pairs of chiral vortex states.

[0023] Figures 2A-2D illustrate the four potential magnetic charges in the honeycomb lattice, shown in Figure 1A.

[0024] Figure 2A illustrates the "three-in" configuration which leads to a +3Q charge. Figure 2B illustrates the "two-in, one-out" configuration that leads to a +Q charge. Figure 2C illustrates the "one-in, two-out" configuration that leads to a -Q charge. Figure 2D illustrates the "three-out" configuration which leads to a -3Q charge. The propagation of these charges can be affected by applying current to the honeycomb lattice.

[0025] While many applications of spin ice are performed at super low temperatures, the present disclosure has been observed to work at a range of temperatures including 300K, aka room temperature.

[0026] The present disclosure describes a system for providing two charges to a portion of the artificial honeycomb spin ice and receiving a resultant charge in response to the two charges. For the purposes of this discussion, the artificial honeycomb is made up of connecting elements separated by hexagonal cylindrical pores. The hexagonal cylindrical pores have widths that are substantially uniform and an average width that is in a range of, but not limited to, about 15 nm to about 20 nm. The hexagonal cylindrical pores a substantially equispaced. The hexagonal cylindrical pores have an average center-to-center distance that is in a range of, but not limited to, about 25 nm to about 35 nm.

[0027] The connecting elements are made up of a magnetic material layer. The connecting elements have lengths that are substantially uniform. The average length of the conducting elements may be, but is not limited to, about 10 nm to about 15 nm. The widths of the connecting elements are substantially uniform and have an average width that is in the range of, but not limited to, about 4 nm to about 8 nm. The connecting elements have a thickness of the magnetic material. That average thickness of the connecting elements is in a range of, but not limited to, about 2 nm to about 8 nm. In some embodiments, the magnetic artificial honeycomb lattice has a surface area, disregarding the presence of the hexagonal cylindrical pores, which is in a range of, but not limited to, about 100 mm^2 to about 900 mm^2.

[0028] Figure 3 illustrates a system for using the honeycomb lattice shown in Figure 1 as a logic gate. In Figure 3, a honeycomb lattice 305 is built of a specific

thickness. As described herein, having a thickness of about 6 nm, the honeycomb lattice 305 acts as an XOR gate. Having a thickness of about 7 nm causes the honeycomb lattice 305 to act as an OR gate. And having a thickness of about 7.5 nm causes the honeycomb lattice to act as an AND gate. For the purposes of this discussion, the honeycomb lattice 305 is at about 300 degrees Kelvin, aka room temperature. This is the general temperature of most electronics.

[0029] The honeycomb lattice 305 receives two input currents 310 and 315 via two input connectors 320 and 325. For the purposes of this discussion, the input current 1 310 and input current 2 315 are between 50μA and 100μA. However, other current values may be used as well. The honeycomb lattice 305 receives the two input currents 310 and 315 and outputs an output voltage 330. The output voltage 330 changes based upon the two input currents 310 and 315.

[0030] The honeycomb lattice 305 also has a ground connector 335 that connects to the ground and two output current connectors 340 and 345 for the output currents 350 and 355.

[0031] In the example embodiment, the thickness of the magnetic material affects the behavior of the honeycomb lattice. More specifically, by applying two currents to the honeycomb lattice, the system measures an output voltage. In particular, with a thickness of about 6 nm, the honeycomb lattice 305 behaves as an XOR gate. With an input current of 50 or 100μA, the output results react as shown below in TABLE 1.

Case	Input 1 310	Input 2 315	Output Voltage 330	Output
1	0 (Off)	0 (Off)	4 mV	0
2	0 (Off)	1 (On)	-30 mV	1
3	1 (On)	0 (Off)	-40 mV	1
4	1 (On)	1 (On)	4 mV	0

TABLE 1

[0032] In another example, with a thickness of about 7 nm, the honeycomb lattice 305 behaves as an OR gate. With an input current of 50 or 100μA, the output results react as shown below in TABLE 2.

Case	Input 1 310	Input 2 315	Output Voltage 330	Output
1	0 (Off)	0 (Off)	3 mV	0
2	0 (Off)	1 (On)	-20 mV	1
3	1 (On)	0 (Off)	-20 mV	1
4	1 (On)	1 (On)	-30 mV	2

TABLE 2

[0033] In a further example, with a thickness of about 7.5 nm, the honeycomb lattice 305 behaves as an AND gate. With an input current of 50 or 100μA, the output results react as shown below in TABLE 3.

Case	Input 1 310	Input 2 315	Output Voltage 330	Output
1	0 (Off)	0 (Off)	3 mV	0
2	0 (Off)	1 (On)	-10 mV	0
3	1 (On)	0 (Off)	-10 mV	0
4	1 (On)	1 (On)	-50 mV	1

TABLE 3

[0001] Figure 4 illustrates a system for using multiple honeycomb lattices 305 shown in Figure 1 to build an algebraic logic unit. More specifically, these honeycomb lattices 305 and 307 may be combined to build an algebraic logic unit (ALU). For example,

honeycomb lattices 305 and 307 are of different thicknesses to act as different logical gates. The XOR, OR, and AND gates may be combined to act as other gates and therefore expanded into an ALU.

ADDITIONAL CONSIDERATIONS

[0002] Example embodiments of honeycomb lattice systems and methods are described above in detail. The systems and methods are not limited to the specific embodiments described herein, but rather, components of the system and methods may be used independently and separately from other components described herein. For example, the honeycomb lattices described herein may be used with other honeycomb lattices to generate algebraic logic units.

[0003] As used herein, an element or step recited in the singular and proceeded with the word "a" or "an" should be understood as not excluding plural elements or steps, unless such exclusion is explicitly recited. Furthermore, references to "example" or "one example" of the present disclosure are not intended to be interpreted as excluding the existence of additional examples that also incorporate the recited features. Further, to the extent that terms "includes," "including," "has," "contains," and variants thereof are used herein, such terms are intended to be inclusive in a manner similar to the term "comprises" as an open transition word without precluding any additional or other elements.

[0004] Furthermore, as used herein, the term "real-time" refers to at least one of the time of occurrence of the associated events, the time of measurement and collection of predetermined data, the time to process the data, and the time of a system response to the events and the environment. In the examples described herein, these activities and events occur substantially instantaneously.

[0005] The patent claims at the end of this document are not intended to be construed under 35 U.S.C. § 112(f) unless traditional means-plus-function language is expressly recited, such as "means for" or "step for" language being expressly recited in the claim(s).

[0006] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the

invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

WHAT IS CLAIMED IS:

1. A magnetic artificial honeycomb lattice comprising a multiplicity of connecting elements separated by hexagonal cylindrical pores, wherein:

(a) the hexagonal cylindrical pores:

(i) have widths that are substantially uniform; and

(ii) are substantially equispaced;

(b) the connecting elements comprise a magnetic material layer, and the connecting elements have:

(i) lengths that are substantially uniform;

(ii) widths that are substantially uniform; and

(iii) a thickness of the magnetic material layer that is substantially uniform and an average thickness; and

(c) the magnetic artificial honeycomb lattice is configured to receive two input currents and configured to output an output voltage based upon the two input currents.

2. The magnetic artificial honeycomb lattice of Claim 1, wherein the two input currents include a first input current and a second input current.

3. The magnetic artificial honeycomb lattice of Claim 2, wherein the first input current and the second input current are in a range of about 50 μA to 100 μA.

4. The magnetic artificial honeycomb lattice of Claim 2, wherein the thickness of the magnetic material layer is about 6 nm.

5. The magnetic artificial honeycomb lattice of Claim 4, wherein the honeycomb lattice functions as an XOR gate.

6. The magnetic artificial honeycomb lattice of Claim 4, wherein when the first input current is off and the second input current is off, the output voltage has an absolute value of 10 mV or less.

7. The magnetic artificial honeycomb lattice of Claim 4, wherein when one of the first input current and the second input current is active while the other is off, the output voltage has an absolute value of 20 mV or more.

8. The magnetic artificial honeycomb lattice of Claim 4, wherein when the first input current is on and the second input current are on, the output voltage has an absolute value of 10 mV or less.

9. The magnetic artificial honeycomb lattice of Claim 2, wherein the thickness of the magnetic material layer is about 6.5 nm.

10. The magnetic artificial honeycomb lattice of Claim 9, wherein the honeycomb lattice functions as an OR gate.

11. The magnetic artificial honeycomb lattice of Claim 9, wherein when the first input current is off and the second input current is off, the output voltage has an absolute value of 10 mV or less.

12. The magnetic artificial honeycomb lattice of Claim 9, wherein when at least one of the first input current and the second input current is active, the output voltage has an absolute value of 20 mV or more.

13. The magnetic artificial honeycomb lattice of Claim 2, wherein the thickness of the magnetic material layer is about 7.5 nm.

14. The magnetic artificial honeycomb lattice of Claim 13, wherein the honeycomb lattice functions as an AND gate.

15. The magnetic artificial honeycomb lattice of Claim 13, wherein when the first input current is off and the second input current is off, the output voltage has an absolute value of 10 mV or less.

16. The magnetic artificial honeycomb lattice of Claim 13, wherein when one of the first input current and the second input current is active while the other is off, the output voltage has an absolute value of 10 mV or less.

17. The magnetic artificial honeycomb lattice of Claim 13, wherein when the first input current is on and the second input current are on, the output voltage has an absolute value of 20 mV or more.

18. The magnetic artificial honeycomb lattice of Claim 1, wherein one or more sections of honeycomb lattice are combined to make an algorithmic logic unit.

19. The magnetic artificial honeycomb lattice of claim 1, wherein the magnetic material is selected from the group consisting of nickel, iron, cobalt, molybdenum, one or more Permalloys, and combinations or mixtures, or alloys thereof.

20. A method of making a making a magnetic artificial honeycomb lattice, the method comprising depositing a layer of magnetic material on a substrate, wherein:

the substrate comprises an artificial honeycomb lattice topography, wherein the artificial lattice topography comprises a multiplicity of connecting elements separated by hexagonal cylindrical pores, wherein:

(a) the hexagonal cylindrical pores:

(i) have widths that are substantially uniform; and

(ii) are substantially equispaced;

(b) the connecting elements comprise a magnetic material layer, and the connecting elements have:

(i) lengths that are substantially uniform;

(ii) widths that are substantially uniform; and

(iii) a thickness of the magnetic material layer that is substantially uniform and an average thickness; and

(c) the magnetic artificial honeycomb lattice is configured to receive two input currents and configured to output an output voltage based upon the two input currents.