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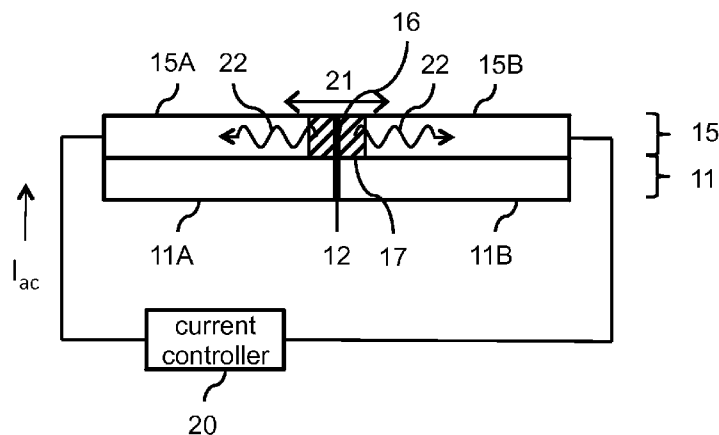


Fig. 2A

(57) Abstract: The disclosed magnonic element for producing spin wave emissions comprises a ferromagnetic material zone (15) containing at least one pinned magnetic domain wall (16) and an electric actuator, e.g. providing an AC driving current, adapted to oscillate the pinned magnetic domain wall at an oscillation frequency for emitting spin waves having a frequency corresponding to said oscillation frequency. Preferably, adjacent to the ferromagnetic material zone a ferroelectric coupling zone (11) is arranged so as to induce said pinned magnetic domain wall and allow for AC voltage excitation. The element can be used as spin wave emitting element in a magnonic logic component.

Element for producing spin waves and logic component comprising such element**Field of the Invention**

The invention relates to magnonic elements, i.e. elements taking advantage of magnetic waves known as spin waves. In addition, the invention relates to logic components
5 utilizing such element. The invention can be used in nanoelectronic devices utilized in information and communication technology, for example.

Background

Modern information and communication technology (ICT) has experienced vast advancements during recent decades thanks to miniaturization in semiconductor
10 electronics and progress in optical (photonic) technologies. Severe challenges are, however, foreseen in nanoelectronics when further downscaling (following Moore's law) leads to more and more heat dissipation per unit area. Therefore, ICT demands new materials for post-silicon computing. Novel technologies and complementary logic circuits need to be developed to overtake special-task data processing that challenges
15 semiconductor-based processors (e.g. pattern recognition and image processing). High-speed optical data processing cannot meet this demand as it does not allow for circuits with the ultrasmall feature sizes known from semiconductor technology due to the relatively large photonic wavelengths. Moreover, although powerful schemes for computing have been discussed since decades, photonic materials and devices have not yet reached a
20 mature state for computing purposes. One major obstacle is the lack of optical components for nanoscale interconnections in existing electronics.

To fulfill future requirements for data transmission and processing rates with low power consumption, a paradigm shift away from purely charge-based electronics is needed. Recently, post-silicon computing with spins and magnets has been identified as a
25 promising route. Here, sequential data processing is still relevant and might limit the bandwidth. Collective spin wave (SW) excitations (magnons) in tailored magnets go beyond this approach and offer low power parallel data processing in cellular networks, thereby optimizing computationally demanding tasks like image processing and speech recognition. Interestingly, contrary to light waves, the wavelength of SWs matches the
30 nanomanufacturing space scales at GHz frequencies. So far, standard approaches for SW

excitation utilize strip-line antennas and spin-transfer torque nanopillars (point contacts). One example of the former type of is presented in Chumak, A. V. et al, *Magnon transistor for all-magnon data processing*, Nat. Commun. 5:4700 doi: 10.1038/ncomms5700 (2014). The SWs in this publication are produced using a microstrip antenna, after which the
5 waves propagate through an yttrium iron garnet strip with periodically modulated thickness. An example of the latter type is disclosed in WO 2014/142740, which discloses a spin oscillator device based on spin-transfer torque effect and taking advantage of nanocontacts on a magnetic films so as to provide so-called “magnetic droplets”, i.e. solitons.

- 10 Thin film bi-layer structures with polarized ferroelectric and ferromagnetic zones that can be used for producing spin waves are in general discussed in articles by Lahtinen, T. H. E. et al, *Electric-field control of magnetic domain wall motion and local magnetization reversal*, Sci. Rep. 2, 2012 and Van de Wiele, B. et al, *Electric field driven magnetic domain wall motion in ferromagnetic-ferroelectric heterostructures*, Applied Physics
15 Letters 104, 2014. The latter one discusses spin wave emissions produced by moving magnetic domain walls at high velocities above a threshold velocity of about 1500 m/s, whereby a spin wave emission phenomenon similar to breaking the sound wall for acoustic waves or Cherenkov effect for moving charges takes place. The emission process is not well controllable and it does not occur at a well-defined physical location. Also, no
20 practically feasible implementations suitable for logic circuits, for example, are disclosed.

Existing techniques for spin wave excitation suffer from several disadvantages. In particular, they are not generally suited for producing short wavelength spin waves, in particular with a wavelength of 1 μm or less. Most of them are also not energy efficient as they require high current densities to drive magnetization oscillations, making the
25 generation of spin waves costly and the device itself fragile. Moreover, the minimum spin wave wavelength is typically determined by the size of the antenna or pillar and is therefore limited by lithographic resolution. The emission of short-wavelength spin waves that are compatible with device miniaturization is therefore problematic. Also, the spectrum of emitted spin waves is rather broad or the emission process is otherwise not
30 well controllable, which complicates the implementation of logic circuits.

Thus, there is a need for providing improved sources of spin waves.

Summary of the Invention

It is an aim of the invention to overcome at least some of the abovementioned disadvantages and to provide a practically feasible element capable of emitting spin waves of desired wavelength, in particular short wavelength spin waves.

- 5 Further aims are to provide a spin wave emitter element, which provides monochromatic spin waves, and to provide an energy efficient spin wave emitter element.

A particular aim is to provide an element, which suits as a building block of a coherent spin wave source, and a logic component comprising such source.

- 10 The invention is based on oscillating a pinned magnetic domain wall contained in magnetic material using electric oscillatory actuation so as to pump energy to the domain wall. As a result, spin waves are emitted from the domain wall at the frequency of the oscillatory actuation.

- 15 The invention thus provides a magnonic element for producing spin wave emissions, the element comprising at least one magnetic material zone containing at least one pinned magnetic domain wall capable of oscillating and an electric oscillatory actuator adapted to oscillate the pinned magnetic domain wall at an oscillation frequency for emitting spin waves therefrom at said oscillation frequency.

- 20 In particular, the magnetic domain wall can be pinned in a zone of ferromagnetic material by a magnetic anisotropy boundary. The anisotropy boundary, for its part, can be induced by a suitable coupling zone, for example an underlayer structure, underlayer structure onto which the ferromagnetic zone is arranged as a layer, which is optionally patterned as an elongated wire. Detailed embodiments are discussed below.

- 25 Further, the invention provides a magnonic logic component comprises a first magnonic element according of the kind described above for emitting coherent spin waves, at least one logic element capable of interacting with the spin waves emitted, and a second magnonic element for detecting the spin waves emitted.

More specifically, the invention is defined by what is stated in the independent claims.

The invention provides significant advantages. In particular, the invention allows for emitting short wavelength spin waves, as the wavelength is dependent on the frequency of oscillation. Electric actuation suits for oscillation at frequencies up to at least 100 GHz, whereby very short wavelength spin waves can be produced. For example, the wavelength
5 can be as short as 1 μm – 15 nm. Particular advantages in this respect are gained when the magnetic domain wall is pinned by a narrow magnetic anisotropy boundary.

Due to electrical actuation, the wavelength of the spin waves is also easily tunable by the frequency of the actuator. In particular, the actuator can provide an AC driving signal, whose frequency, typically 100 MHz – 100 GHz, directly determines the wavelength,
10 wave vector and group velocity of the resulting spin waves. This type of well-defined emission is herein called monochromatic emission. The actuator can use for example an AC current or an AC electric field to couple with the magnetic domain wall. These kinds of electric actuation techniques are well controllable and allow for emitting spin waves with very well-defined properties.

15 An oscillatory pinned magnetic domain wall allows for low-power emission of spin waves in particular when internal resonance modes of the domain wall are taken advantage of. That is, the element is very energy efficient. A particularly efficient emitter can be achieved if the oscillatory actuator is adapted to couple an AC electric field to a layer under the pinned domain walls is used for bringing the domain walls into oscillatory
20 motion. The efficiency of the process is particularly high when the actuation takes place at a resonance frequency of the magnetic domain wall.

Finally, the present element is not restricted to only one spin wave emitting point but can contain two or more pinned magnetic domain walls, which are oscillated using the electric oscillatory actuation simultaneously and in synchronization, which guarantees full
25 coherence of spin waves originating from different physical locations. This makes the element usable in practical transistors, logic gates, memory devices and the like data processing and/or storage components for ICT purposes, for example. Thus, the element according to the invention can be used as a building block for a new technology platform based on magnonics rather than silicon-based electronics. Of particular importance are
30 implementations where a plurality of magnetic domain walls is induced by the same ferroelectric domain wall -containing underlayer.

The dependent claims are directed to selected embodiments of the invention.

In some embodiments, the at least one magnetic material zone comprises at least one microwire or nanowire in which the pinned magnetic domain wall separates two or more magnetic domains with different magnetization along the length direction of the wire. In
5 some alternative embodiments, the magnetic material zone is provided as a wider layer.

According to some embodiments, the oscillatory actuator is adapted to oscillate the pinned magnetic domain wall at a resonance frequency of the pinned magnetic domain wall, whereby the domain walls efficiently absorb energy for emitting the spin waves. For example, the actuator can be adapted to produce an internal domain wall resonance, such
10 as a local standing spin wave resonance mode, for the oscillating pinned magnetic domain wall. Typically, domain wall structures have many different resonance modes over a broad frequency range. In particular in a nanowire geometry, several resonance frequencies exist.

Moreover, with increasing frequency, i.e. towards shorter spin wave wavelengths, the difference between the resonance frequencies decreases dramatically leading to a quasi-
15 continuous absorption of energy for increasing frequencies. This makes it convenient to find a desired oscillation frequency producing the desired output.

In typical embodiments the oscillation of the pinned magnetic domain wall takes place in a direction perpendicular to the pinned magnetic domain wall, but other modes of oscillation are possible too. In nanowire geometries, the resonant oscillation perpendicular to the
20 domain wall defines the minimum frequency for spin wave emission. At higher frequencies internal domain wall oscillation modes exist that are able to transfer energy from the excitation towards spin waves. This mechanism is of particular importance when efficiently producing high-frequency small-wavelength spin wave emission.

In some embodiments, the oscillation frequency of the actuator is tunable for providing a
25 tunable-wavelength spin wave source.

In some embodiments, the at least one magnetic material zone comprises ferromagnetic material.

In some embodiments, there is provided at least one coupling zone adjacent to the at least magnetic material zone, the coupling zone being capable of inducing the pinned magnetic

domain wall in the at least one magnetic material zone. For example, the at least one magnetic material zone can be provided as a first layer of magnetic material and the coupling zone as second layer having an interface with the first layer, whereby the at least one pinned domain wall is created in the first layer through coupling of the first and second layers at the interface region. Induction of the magnetic domain wall through such mechanism results in abrupt change in anisotropy properties of the magnetic material zone and very local pinning of the magnetic domain wall. This further provides particularly advantageous spin wave emission properties as concerns for example monochromaticity and small wavelength.

- 10 The intrinsic pinning mechanism does not suffer from lithographic limitations and forms a particularly interesting feature of the present technology.

In some embodiments, the magnetic material zone is arranged as a layer of magnetic material on a substrate or other kind of an underlayer capable of inducing said pinned magnetic domain wall in the at least one magnetic material zone. The underlayer itself may for example comprise at least two domains separated by a domain wall, which is coupled to the magnetic material zone. The underlayer may e.g. induce in the magnetic material zone a magnetic anisotropy boundary onto which the magnetic domain walls are pinned. Thus, two magnetic domains with different anisotropy and separated by an anisotropy boundary, are formed.

- 20 A particular example of this kind of an underlayer is a ferroelectric layer with a ferroelectric domain wall separating two ferroelectric domains with different polarizations, each domain inducing a different magnetic anisotropy in ferromagnetic material superimposed on the ferroelectric layer. The ferroelectric domain wall induces a narrow anisotropy boundary on which the induced magnetic domain wall pins. This way, a localized magnetic domain wall over which the magnetization direction changes over a very short distance can be formed. Oscillatory behavior of such magnetic domain wall is also very well defined. Contrary to prior approaches where domain walls are pinned to geometrical constrictions, i.e. notches, this technique accomplishes ferromagnetic domain wall pinning on the nanometer space scale of the ferroelectric domain wall, resulting in sharp well-defined harmonic pinning potentials. In other words, the present kind of spin

wave source is localized and not generally defined by lithographic resolution and tolerances, but the small width of the ferroelectric domain wall.

It should be noted that an underlayer of the kind described above is only one example of suitable coupling zones. Such layer may be placed also on top of the magnetic material layer, or the zones can reside even laterally, provided that there is a coupling between the zones that can induce a pinned magnetic domain wall in the magnetic material zone.

In some embodiments, there are provided a plurality, i.e. at least two magnetic domains walls capable of being oscillated and spin wave emissions are produced simultaneously from at least two magnetic domain walls by oscillating them using electric oscillatory actuation. This can be achieved in various ways. There may for example be a plurality of separate magnetic material zones each containing a magnetic domain wall. In one realization, there is provided a domain wall in the underlayer which is crossed by the plurality of magnetic material zones, whereby the domain wall of the underlayer induces a magnetic domain wall to each such zone. Alternatively or in addition to that, several domain walls can also be formed into a single magnetic material zone. There may for example be several domain walls in the underlayer, each inducing a separate pinned domain wall in a single magnetic material layer crossing the several domain walls.

In some embodiments, the at least one magnetic material zone comprises at least one ferromagnetic nanowire or microwire crossing at least one domain wall of the underlayer, such as the ferroelectric domain wall mentioned above. Thus, a very localized pinned magnetic domain wall is formed. There may also be a plurality of parallel wires crossing a single underlayer domain wall, whereby multiple sources of coherent spin waves are formed. The wires are typically arranged parallel to each other at the location of the underlayer domain wall.

In some embodiments, the two ferroelectric domains separated by the ferroelectric domain wall are orthogonally in-plane polarized, thereby inducing orthogonally magnetized ferromagnetic domains with orthogonally uniaxial magnetic anisotropy and a pinned ferromagnetic domain wall in the ferromagnetic material crossing the domain wall. Other types of induced anisotropy are equally possible, e.g. when there are two ferroelectric domains in the underlayer, one having in-plane polarization and the other having out-of-

plane polarization. This can induce a uniaxial magnetic anisotropy in a ferromagnetic layer on top of the in-plane domain and bi-axial magnetic anisotropy on top of the out-of-plane domain, and a corresponding anisotropy boundary between them. In such a case, a 45 degree angle can exist between the anisotropy axes in the different regions. Moreover,
5 there are many ferroelectric materials and phases that have other domain structures that could be used to create a spin wave emitter.

In some embodiments, the actuator is adapted to apply an alternating electric field through the ferroelectric layer for oscillating the magnetic domain wall (or walls) pinned on the ferroelectric layer. In alternative embodiments, the actuator is adapted to feed alternating
10 current, in particular spin-polarized current, through the magnetic material zone (or zones) and the pinned magnetic domain wall (or walls) contained in them. Both mechanisms result in that the pinned magnetic domain wall (or walls) start to oscillate, whereby energy is pumped thereto for emitting the spin waves.

In the case of elements containing several magnetic domain walls, the electric actuation is
15 adapted to oscillate all or at least some of the domain walls simultaneously. Thus, coherent spin waves are emitted by the domain walls. Practical applications do not require the spin waves emitted being necessarily in the same phase, although they can be. Thus, oscillatory actuation of the domain walls may take place in the same phase or with a known phase difference. For achieving similar wave vectors for the waves it is, however, preferred that
20 the two or more pinned magnetic domain walls are induced by a single ferroelectric domain wall, which the magnetic material zone crosses or several different magnetic material zones cross. Indeed, at least some of the pinned magnetic domain walls can be situated in different magnetic material zones preferably arranged parallel to each other. This is the case for example with two parallel ferromagnetic nanowires crossing a single
25 ferroelectric domain wall.

It is also possible that there is a plurality of successive domain walls in the underlayer, which induce and pin a plurality of magnetic domain walls in a single magnetic layer, such as nanowire, crossing the plurality of domain walls of the underlayer. Identical domain walls of the underlayer ensure identical domain walls in the magnetic layer and thus
30 similar spin waves.

In the present invention, a magnetic domain wall is disclosed that is strongly pinned to a ferroelectric domain wall. In embodiments, the magnetic domain wall can be excited by either an AC electric current or an AC electric field. The excitation can result in a back-and-forth motion of the domain wall, typically over a distance of only a few nanometer, for example a distance of about 0.1 to 50 nm, for example 1 to 10 nm. Thus, the domain wall remains highly localized. The velocity of the domain wall is non-constant during this motion. It continuously oscillates. In addition, in embodiments of the invention, excitation of the domain wall with an AC electric current or an AC electric field induces magnetization precession within the domain wall without actual domain wall displacement. Both oscillation modes result in the emission of spin waves. The frequency of the spin waves is identical to the AC driving frequency.

Next, selected embodiments of the invention and advantages thereof are discussed in more detail with reference to the attached drawings.

Brief Description of the Drawings

Fig. 1A shows a cross-sectional side view of a layer structure according to one embodiment of the invention.

Figs. 1B and 1C show planar views of the layers of Fig. 1A.

Fig. 1D illustrates the behavior of magnetization at the location of the magnetic domain wall in a structure according to Figs. 1A-1C.

Figs. 2A and 2B show oscillatory electric actuators coupled to the structure of Fig. 1A according to embodiments of the invention.

Figs. 3A and 3B show a top view and perspective view, respectively, of two potential structures and oscillatory actuators of coherent spin wave emitting elements according to embodiments of the invention.

Figs. 4A and 4B show a cross-sectional end view and top view, respectively, of an element with two magnetic domain walls pinned by a single underlayer domain wall.

Figs. 5A and 5B show a cross-sectional end view and top view, respectively, of an element with two magnetic domain walls pinned by separate underlayer domain walls.

Fig. 6 schematically illustrates a logic component utilizing a spin wave emitting element according to the invention.

Detailed Description of Embodiments

Definitions

- 5 In a film geometry, the term “domain” (like in “(ferro)magnetic domain” or “ferroelectric domain”) refers to a region of material in which a particular property of interest (magnetization or electric polarization, respectively) is spatially uniform (aligned in a uniform direction). In a micro- or nanowire geometry, the term “domain” refers to a region of the material in which a particular property of interest does not change along the wire
- 10 axis coordinate. A “domain wall” [like in “(ferro)magnetic domain wall” or “ferroelectric domain wall”] is an interface between two different domains, where the property of interest (magnetization or electric polarization, respectively) makes a transition (change of orientation) from one state to another. A zone of material [like “(ferro)magnetic material zone” or “ferroelectric material zone”] can in general contain one or more domains and
- 15 domain walls. Width of a domain wall is defined as the distance over which the transition essentially takes place.

The term ferromagnetic is used in broad sense covering also materials known as ferrimagnetic.

- “Anisotropy boundary” refers to a region, where the symmetry, direction and/or strength of
- 20 the anisotropy of the material changes locally. In particular, an anisotropy boundary, as herein used, is capable of pinning a ferromagnetic domain wall intersecting or located close to the anisotropy boundary.

- “Coupling zone” refers to a zone of material close to the magnetic material zone capable of inducing the pinned magnetic domain wall in the magnetic material zone through physical
- 25 coupling of the zones. Examples of coupling zones include a layer of ferroelectric or antiferromagnetic multiferroic material with a domain wall provided therein. Such layers couple with ferromagnetic material generating the desired pinned ferromagnetic domain wall.

Oscillation of a magnetic domain wall can mean oscillation of its location with respect to its resting location, i.e. location without the actuation. In typical embodiments, the oscillation takes place in a direction perpendicular to the domain wall, for example back and forth along a ferromagnetic (micro or nano)wire containing a magnetic domain wall.

5 The domain wall can be transverse to the direction of the wire or have another orientation. Additionally ‘oscillation’ can also refer to oscillation modes of the magnetization, inside the magnetic domain wall. In typical embodiments, these oscillation modes are standing spin waves localized in the domain wall, e.g. along the direction of the anisotropy boundary.

10 “Coherent” spin waves mean spin waves that have fixed phase relation, i.e, either the same phase or a constant non-zero phase difference.

“Nanowire” is an elongated formation of material whose transverse dimensions are less than 1 μm , in particular 100 nm or less. “Microwire” is an elongated formation of material whose transverse dimensions are 1 μm – 1 mm.

15 As explained above, a magnetic domain wall is disclosed that is strongly pinned to a ferroelectric domain wall. In embodiments, the magnetic domain wall is excited and excitation can result in a back-and-forth motion of the domain wall, typically over a distance of only a few nanometer. Thus, the domain wall remains highly localized. The velocity of the domain wall is non-constant during this motion. Thus, the terms “moving”
 20 and “exciting” basically refer to the same phenomenon, and the term “moving” is to be understood as covering also the action of “exciting” the wall.

Ferroelectric-ferromagnetic bi-layer domain wall spin wave emitter

The following description concentrates on describing an embodiment of the invention comprising a magnonic element with a ferromagnetic layer on a ferroelectric layer, which
 25 induces a magnetic domain wall in the ferromagnetic layer and pins it on an anisotropy boundary. First, single magnetic domain wall emitters are discussed separately and then examples of coherent two-domain-wall emitters are presented.

Figs. 1A-C show a structure with a ferroelectric layer 11 comprising a first ferroelectric domain 11A and a second ferroelectric domain 11B, whose polarizations are different. The

domains 11A, 11B are separated by a ferroelectric domain wall 12, which is perpendicular to the plane of the layer. On top of the ferroelectric layer 11, there is provided a ferromagnetic layer 15. Coupling of the two layers 11, 15, such as strain transfer at the interface between them, induces a magnetic anisotropy in the ferromagnetic layer 15, which changes abruptly in direction, strength and/or symmetry at the ferroelectric domain wall 12, creating a magnetic anisotropy boundary 16 in the ferromagnetic layer 15 on top of the ferroelectric domain wall 12. A magnetic domain wall 17 is pinned by this anisotropy boundary 16, defining two magnetic domains 15A, 15B and acts as a spin wave emitting feature, when brought into oscillation. Thus, the domain wall 12 of the ferroelectric layer 11 is “imprinted” to the ferromagnetic layer 15.

This is only one possible example of the ferromagnetic and ferroelectric configuration. Many other ferroelectric domain configurations could be used to create ferromagnetic domains and a pinned magnetic domain wall in the ferromagnetic layer. Also, the parallel alignment between in-plane polarization direction 18A, 18B and the in-plane magnetization direction 19A, 19B can be different depending on the magnetostriction constant of the ferromagnetic layer (in case of strain transfer) and/or applied magnetic field. Typically, there is at least 30 degrees angle difference, in particular 45 degrees or more between the polarization angles of the ferroelectric domains 11A, 11B. In the example, illustrated in Figs. 1B and 1C, the angle difference is 90 degrees, which ensures strong induction of the magnetic domain wall 17. In typical embodiments, the angle difference takes place in the plane of the layer 11, but can also contain an out-of-plane component or be entirely out-of-plane. In summary, the polarizations in the two ferroelectric domains need to be different, but many different configurations depending on the type of domain structure and ferroelectric phase and/or material are possible.

To describe the imprinting mechanism in more detail, the polarization in the ferroelectric domains 11A, 11B elongates the structural units of the layer. Via inverse magnetostriction, the associated strain induces a uniaxial anisotropy in the ferromagnetic layer, defining there the two ferromagnetic domains 15A, 15B. As a result, ferroelectric domain structure is fully imprinted in the ferromagnetic layer and the ferromagnetic domain wall 16 is also strongly pinned. In the described structure, the ferroelectric layer 11 determines the static equilibrium magnetization state in the ferromagnetic layer 15: while in the ferromagnetic domains 15A, 15B the magnetization direction is determined by a competition between the

uniaxial anisotropy directions and strengths on the one hand and geometry-induced easy magnetization directions (known as shape anisotropy) on the other hand. At the anisotropy boundary the magnetic anisotropy changes orientation over a very short distance. Due to the abrupt change of magnetic anisotropy at the anisotropy boundary 16, the ferromagnetic domain wall 17 is firmly pinned.

It should also be noted that the oscillating pinned magnetic domain wall required for emission of spin waves can also be created even without a ferroelectric layer as the underlayer. Coupling between the underlayer and the ferromagnetic layer can be mediated via strain as described above by way of example, but other coupling mechanisms are also possible. Variations include in particular exchange bias, local ion migration and charge accumulation, which are all covered by the term “induce”. Some specific examples are described later in this document.

The ferroelectric domain wall 12 in the ferroelectric layer 11 and thus the anisotropy boundary 16 pinning the magnetic domain wall 17 in the ferromagnetic layer 15 are very narrow. This extreme lateral confinement enables the emission of short wavelength spin waves. The magnetic domain wall 17 is typically broader than the ferroelectric domain wall 12 and the anisotropy boundary 16, as illustrated in the figures. To give some non-limiting examples, the width of the pinned magnetic domain wall 17 may range from only few nanometers to at most 1000 nm, such as 5 – 500 nm.

Fig. 1D illustrates how the direction of magnetization changes uniaxially over this small width by 90 degrees in an exemplary infinite film geometry. With different configurations of the underlayer and overall element geometry or in the presence of an external magnetic field, the magnetization map can be also different.

In some embodiments, the ferromagnetic layer 15 is narrow also in the transverse lateral direction, i.e. the lateral direction parallel to the direction of the domain wall 17. In particular, the layers may be provided in the form of microwires (width 1 – 1000 μm) or nanowires (width less than 1000 nm).

The ferromagnetic material may comprise e.g. Co, Fe, Ni or an alloy containing one or more of these materials. One specific example of suitable materials is CoFe. There are also many other crystalline and amorphous ferromagnetic materials that suit for the present use.

The ferroelectric material may comprise e.g. BaTiO₃, PbTiO₃, LiTaO₃, lead zirconium titanate (PZT), triglycerine sulfate (TGS), or polyvinylidene fluoride (PVDF).

- Fig. 2A shows one possibility for actuating the oscillation of the magnetic domain wall 17, i.e. injecting an alternating current I_{ac} through the ferromagnetic material layer 15 using a current controlling unit 20. The alternating current I_{ac} may be spin-polarized. In this example, the current flows perpendicular to the domain wall 17. This causes the magnetic domain wall 16 to oscillate in the pinning potential of the anisotropy boundary. Above a critical frequency, this leads to the emission of spin waves 22 at the frequency of the ac driving current. In a film geometry this spin wave emission can originate in the oscillatory back-and-forth motion of the domain wall done at the same frequency of the excitation. Each excitation cycle, the potential energy difference between extreme and zero domain wall displacement (in the x-direction of Fig. 2) is dissipated by the oscillator by emitting spin waves and internal damping. In a microwire and nanowire geometry, confinement effects allow additional domain wall oscillations corresponding to the existence of standing spin wave modes localized inside the domain walls and beating at the excitation frequency. Each excitation cycle, the potential energy stored in the standing spin waves is dissipated by the emitting spin waves and internal damping. In both cases, the wavelength of the emitted spin waves 22 decreases with increasing frequency, providing a high degree of tunability.
- Depending on the configuration, the oscillation of the domain wall 17 due to the injected current I_{ac} may take place via the spin transfer torque effect, spin Hall effect or Rashba effect, to mention some examples. In particular if one of the two latter effects is taken advantage of, there may be provided an additional metallic layer with large spin-orbit coupling in contact with the ferromagnetic layer.
- With reference to Fig. 2B, alternatively to passing an AC electric current through the ferromagnetic domain wall, the actuator may be based on the use of an AC electric field applied to the ferroelectric layer 11 using a voltage controlling unit 23. This field causes the ferroelectric domain wall 12 in the ferroelectric layer 11 to oscillate. Because of coupling between the ferroelectric layer 11 and the ferromagnetic layer 15, the oscillatory motion of the ferroelectric domain wall 12 is mimicked by the anisotropy boundary 16 in the ferromagnetic layer 15. The oscillations of the anisotropy boundary 16 induce

oscillations of the ferromagnetic domain wall 17 in the ferromagnetic layer 11 at the same frequency. Again, above a critical frequency this leads to the emission of spin waves 22 at the frequency of the AC electric field. Similarly, the wavelength of the emitted spin waves decreases with increasing frequency, whereby also this actuation scheme offers high
5 degree of tunability. Since the electric current flowing through the device is much reduced in this realization, because ferroelectric layers are insulating, spin wave emission at lower energy consumption levels can be obtained.

It should be noted that the application of an alternating voltage can be along many directions, depending on the polarization configuration in the ferroelectric layer. The
10 illustration indicates the application of an alternating voltage along the out-of-plane direction. However, depending on the configuration, the voltage may be along the in-plane direction or any other direction too.

The inventive spin wave emission mechanism is briefly explained below. When exciting oscillatory motion of the ferromagnetic domain wall with for example an alternating spin-
15 polarized current, one continuously pumps energy in the domain wall oscillator. Each excitation cycle, the potential energy difference between extreme and zero domain wall displacement or between maximum and zero amplitude of internal domain wall standing spin wave profiles is dissipated by the oscillator by emitting spin waves and internal damping. The generated spin waves generally propagate perpendicular to the domain wall,
20 i.e. with a wave front parallel to the domain wall. The ferromagnetic layer 15 acts as a spin wave waveguide. The ferromagnetic domain wall is preferably oscillated at its resonance frequency, whereby actuation energy is efficiently absorbed and dissipated by the domain wall oscillator by emitting large-amplitude spin waves into the nanowire. It should be noted that a nanowire-shaped domain wall oscillator has a plurality of possible resonance
25 modes that can be used, in particular between 1 and 100 GHz. In particular in a nanowire geometry, a huge number of internal domain wall resonances exists. The frequency step between these resonances decreases rapidly at higher frequencies leading to an excitation efficiency that only moderately depends on the frequency.

Figs 3A and 3B illustrate coherent spin wave emitters containing two spin wave sources
30 and the two different actuation mechanism discussed above applied to them. Both variations comprise similar layer structures having a ferroelectric layer with two domains

31A, 31B; 41A, 41B like those discussed above with reference to Figs. 1 and 2. Instead of only one ferromagnetic layer, there are provided two separate layers 35, 37; 45, 47 which are parallel to each other and cross the ferroelectric domain wall 32; 42 between the ferroelectric domains 31A, 31B; 41A, 41B perpendicularly. The layers 35, 37; 45, 47 are preferably arranged as parallel nanowires. In both parallel nanowires, the magnetization distribution is fixed by the strong anisotropy induced by the ferroelectric layer. Both layers act as ferromagnetic spin wave waveguides into which identical domain walls are induced by the ferroelectric domain wall underneath them by the mechanism discussed above. To be noted is that the spin waves are generated by domain wall oscillators pinned to the same ferroelectric domain wall.

Fig. 3A illustrates an actuation mechanism where an AC electrical current (I_{ac}) fed from a current controller 33 through the waveguides 35, 37 makes, via the spin-transfer-torque effect, the respective domain walls oscillate while emitting spin waves with identical frequency. Identical waveguide dimensions and electrical currents (same waveform, phase and amplitude) guarantee full coherence between the spin wave sources. It is, however an advantage of this actuation mechanism that a phase difference in the actuation currents directed to each waveguide 35, 37 can be provided, resulting in an identical phase difference between the spin waves.

Fig. 3B illustrates an actuation mechanism where an AC electrical field applied on the ferroelectric layer 41A, 41B from an AC voltage (V_{ac}) controller 43 makes the anisotropy boundary together with the ferromagnetic domain walls of the waveguides 45, 47 oscillate. Again, spin waves are emitted at the same frequency and identical waveguide dimensions guarantee full coherence between the spin wave sources. This embodiment has the advantage of being energy-efficient, as the ferroelectric layer is generally insulating and therefore losses are low.

The current controller 20, 33 or voltage controller 23, 43 can be adapted to provide a fixed-frequency driving signal for providing a fixed-wavelength spin wave source or comprise means for tuning the frequency of the driving signal for achieving a wavelength-tunable spin wave source.

Figs. 4A, 4B, 5A and 5B illustrate two more detailed examples on how to create multiple spin wave emitters allowing for coherent spin wave emission. The example of Figs. 4A and 4B comprises two ferromagnetic nanowires 35A, 35B; 37A, 37B are patterned on top of a ferroelectric layer 31A, 31B with a ferroelectric domain wall 32. A ferromagnetic domain wall 36, 38 is pinned on top of the ferroelectric domain wall 32 in each of the ferromagnetic nanowires 35A, 35B; 37A, 37B via coupling between the ferroelectric layer and the ferromagnetic nanowires as described before. The ferromagnetic domain walls can be brought into oscillatory motion using an alternating current or an alternating voltage, as also presented above, leading to the emission of spin waves in the ferromagnetic nanowires 35A, 35B; 37A, 37B. In case of electric current actuation, the phase between the spin waves in the two nanowires 35A, 35B; 37A, 37B can be tuned by controlling the phase of electric current in ferromagnetic nanowire 35A, 35B and 37A, 37B. Other realizations are also possible. For example, the schematic shows the ferroelectric layer in film geometry. It is also possible to pattern both the ferromagnetic layer and the ferroelectric layer in a nanowire geometry or some other geometry.

In the variation of Figs. 5A and 5B, two ferromagnetic domain walls 77A, 77B in a ferromagnetic nanowire 75A, 75B, 75C are pinned on top of two ferroelectric domain walls 62A, 62B in a ferroelectric layer 61A, 61B, 61C via the previously described coupling mechanism. The ferromagnetic domain walls 77A, 77B can be brought into oscillatory motion using an alternating current or an alternating voltage, as in the previous examples, leading to the emission of spin waves in the ferromagnetic nanowire 75A, 75B, 75C. Other realizations are possible in this case too. The ferromagnetic layer could for example be a continuous film in the case of electric-field actuation or both the ferromagnetic layer and the ferroelectric layer could be patterned into a nanowire geometry or some other geometry.

In the illustrated embodiments, the number of ferromagnetic domain walls is two. The concepts of Fig. 4A, 4B and 5A, 5B can be extended to oscillating ferromagnetic domain wall spin wave emitters with more than two domain walls as the spin wave emission points by utilizing more than two parallel nanowires crossing a single ferroelectric domain wall and/or more than two ferroelectric domain walls which a single ferromagnetic wire crosses. The number of domain walls in such variations can be for example 3 – 10. The concepts shown in Figs. 4A, 4B and 5A, 5B can also be combined. That is, there may be

both a plurality of ferromagnetic nanowires and a plurality of magnetic domain wall inducing ferroelectric domain walls underneath them.

An important aspect is the highly monochromatic nature of the spin waves achievable by structures disclosed herein. In particular, spin waves in parallel nanowires with domain wall oscillators pinned to the same ferroelectric domain wall have identical dispersion properties. When applying currents with identical frequency to these nanowires the domain wall oscillators emit monochromatic coherent spin waves in all wires. If desired, a fixed phase relation between the spin waves in different nanowires can be introduced by tuning the phase of the individual excitation currents (using the configuration of Fig. 3A).

- 10 Monochromaticity of spin waves and coherence between sources are key points in the development of Mach-Zehnder based logic elements and sensors.

Alternative domain wall spin wave emitter structures

- 15 Alternatively to the ferroelectric-ferromagnetic bi-layers structure discussed above, anisotropy boundaries, and thus pinned magnetic domain walls, capable of emitting spin waves can be formed in other ways. Some of them are briefly discussed below.

In some alternative embodiments, the ferroelectric layer is replaced by an antiferromagnetic ferroelectric (multiferroic) layer, whereby an exchange bias between the antiferromagnetic multiferroic layer and the ferromagnetic layer forms the required anisotropy boundary.

- 20 In some embodiments, the ferromagnetic layer is grown onto another pre-patterned substrate capable of inducing the anisotropy boundary.

In some embodiments, local ion implantation or proton irradiation is applied to the ferromagnetic layer, using an implantation or irradiation scheme capable of providing an anisotropy boundary in the ferromagnetic layer.

- 25 In some embodiments, there is provided local electric gating of a ferromagnetic film, using ionic or charge effects to provide the anisotropy boundary.

The AC current injection actuation scheme illustrated in Figs. 2A and 3A and discussed above in more detail is applicable also to all these alternative structures. The AC field

actuation scheme illustrated in Figs. 2B and 3B and discussed above in more detail is applicable to the alternative structure containing the antiferromagnetic ferroelectric (multiferroic) layer underneath the ferromagnetic layer. Multiferroic materials are also insulating by nature, whereby low energy consumption levels are achievable by the AC field actuation.

In some embodiments, there is provided a plurality of ferroelectric domain walls parallel to each other and a single nanowire crossing the plurality of domain walls, thus defining identical domain wall oscillators in one-and-the-same nanowire. With this kind of coherent spin wave sources dispersion band gaps, for example, can be provided without intervening in the nanowire geometry, again alleviating lithographic restrictions.

Logic components utilizing the domain wall spin wave emitter

Fig. 6 shows a schematic example of a logic component 600 utilizing a spin wave source element 610 capable of emitting two coherent spin waves 690A, 690B upon electrical actuation initiated via a driving signal input 620. In addition, the component 600 comprises, two logic inputs 640A, 640B connected to logic elements 630A, 630B capable of interacting with the spin waves 690A, 690B, respectively. Finally, the spin wave(s) passing the logic elements are detected at a detector element 670 for providing an output signal at an output 680 of the component 600.

The source element 610 can be for example a coherent double-nanowire source as discussed above with reference to Fig. 3A, 3B, 4A or 4B or any variation thereof. The logic elements 630A, 630B can be functionally connected to the nanowire waveguides so as to provide a desired output of the logic component depending on signals provided at the logic inputs.

The logic component may utilize the Mach-Zehnder principle.

Using this principle, a logic gate performing an AND, NAND, OR, XOR or XNOR operation, for example, can be implemented. By suitable modification, but using the same principle, a magnonic transistor with magnonic source, gate and drain terminals can be implemented.

Based on the above, a magnonic element is provided for producing spin wave emissions, comprising at least one magnetic material zone containing at least one pinned magnetic domain wall, and an actuator for exciting or moving the at least one pinned magnetic domain wall, the actuator comprising an electric actuator adapted to oscillate the at least one pinned magnetic domain wall at an oscillation frequency for emitting spin waves having a frequency corresponding to said oscillation frequency.

Further, a magnonic logic component of the present technology comprises a first magnonic element for emitting spin waves, at least one logic element capable of interacting with the spin waves emitted, and a second magnonic element for detecting the spin waves emitted by the first magnonic element, wherein first magnonic element is an element of the above kind.

It is to be understood that the embodiments of the invention disclosed are not limited to the particular structures, process steps, or materials disclosed herein, but are extended to equivalents thereof as would be recognized by those ordinarily skilled in the relevant arts. It should also be understood that terminology employed herein is used for the purpose of describing particular embodiments only and is not intended to be limiting.

Reference throughout this specification to one embodiment or an embodiment means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases “in one embodiment” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment. Where reference is made to a numerical value using a term such as, for example, about or substantially, the exact numerical value is also disclosed.

As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be construed as a de facto equivalent of any other member of the same list solely based on their presentation in a common group without indications to the contrary. In addition, various embodiments and example of the present invention may be referred to herein along with alternatives for the

various components thereof. It is understood that such embodiments, examples, and alternatives are not to be construed as de facto equivalents of one another, but are to be considered as separate and autonomous representations of the present invention.

Furthermore, the described features, structures, or characteristics may be combined in any
5 suitable manner in one or more embodiments. In the following description, numerous specific details are provided, such as examples of lengths, widths, shapes, etc., to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that the invention can be practiced without one or more of the specific details, or with other methods, components, materials, etc. In other instances,
10 well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the invention.

While the forgoing examples are illustrative of the principles of the present invention in one or more particular applications, it will be apparent to those of ordinary skill in the art that numerous modifications in form, usage and details of implementation can be made
15 without the exercise of inventive faculty, and without departing from the principles and concepts of the invention. Accordingly, it is not intended that the invention be limited, except as by the claims set forth below.

The verbs “to comprise” and “to include” are used in this document as open limitations that neither exclude nor require the existence of also un-recited features. The features
20 recited in depending claims are mutually freely combinable unless otherwise explicitly stated. Furthermore, it is to be understood that the use of “a” or “an”, that is, a singular form, throughout this document does not exclude a plurality.

Industrial Applicability

25 The present nanoelectronic devices can be utilized in information and communication technology. Thus, the present element, in particular when containing two or more coherent spin wave emitting spots, can be used as a spin wave emitting element in a magnonic transistor, a magnonic logic gate, such as a gate performing an AND, NAND, OR, XOR or XNOR operation, a magnonic memory device or magnonic crystal.

Reference Signs List

	10	spin wave
	11, 15	ferroelectric layers
5	11A	first ferroelectric domain
	11B	second ferroelectric domain
	12	ferroelectric domain wall
	16	magnetic anisotropy boundary
	17	magnetic domain wall
10	15A	first magnetic domain
	15B	second magnetic domain
	18A, 18B	in-plane polarization direction
	19A, 19B	in-plane magnetization direction
	20; 33	current controlling unit
15	22	spin waves
	23; 43	voltage controlling unit
	31A, 31B	ferroelectric layer
	41A, 41B	ferroelectric layer
	35, 37	waveguides ferromagnetic layer
20	45, 47	waveguides ferromagnetic layer
	32; 42	ferroelectric domain wall
	35A, 35B	ferromagnetic nanowires
	36, 38	ferromagnetic domain wall
	37A, 37B	ferromagnetic nanowires
25	77A, 77B	ferromagnetic domain walls
	75A, 7B, 75C	ferromagnetic nanowire
	62A, 62B	ferroelectric domain walls
	61A, 61B, 61C	ferroelectric layer

Citation List**Patent Literature**

WO 2014/142740

Non-Patent Literature

- 5 Chumak, A. V. et al, *Magnon transistor for all-magnon data processing*, Nat. Commun. 5:4700 doi: 10.1038/ncomms5700 (2014).

Lahtinen, T. H. E. et al, *Electric-field control of magnetic domain wall motion and local magnetization reversal*, Sci. Rep. 2, 2012.

- Van de Wiele, B. et al, *Electric field driven magnetic domain wall motion in*
10 *ferromagnetic-ferroelectric heterostructures*, Applied Physics Letters 104, 2014.

Claims

1. A magnonic element for producing spin wave emissions, comprising
 - at least one magnetic material zone containing at least one pinned magnetic domain wall, and
- 5 – an actuator for moving the at least one pinned magnetic domain wall,
characterized in that
 - the actuator comprises an electric actuator adapted to oscillate the at least one pinned magnetic domain wall at an oscillation frequency for emitting spin waves having a frequency corresponding to said oscillation frequency.
- 10 2. The element according to claim 1, **characterized** in that there is provided at least one coupling zone adjacent to the at least magnetic material zone, the coupling zone being capable of coupling with the magnetic material zone so as to induce said pinned magnetic domain wall therein.
- 15 3. The element according to claim 2, **characterized** in that the at least one magnetic material zone is provided as a first layer of magnetic material and the coupling zone as second layer having an interface with the first layer, whereby the at least one pinned domain wall is created in the first layer through coupling of the first and second layer at the interface.
- 20 4. The element according to claim 2 or 3, **characterized** in that the electric actuator comprises means for applying an alternating electric field through the coupling zone for oscillating the at least one pinned magnetic domain wall.
- 25 5. The element according to any of claims 2 – 4, **characterized** in that the coupling zone comprises a ferroelectric layer comprising a ferroelectric domain wall separating two ferroelectric domains with different polarizations, whereby the at least one ferroelectric domain wall induces said at least one pinned magnetic domain wall.
6. The element according to claim 5, **characterized** in that the two ferroelectric domains are orthogonally polarized, thereby inducing orthogonally magnetized ferromagnetic domains with orthogonal uniaxial magnetic anisotropy and a pinned ferromagnetic domain wall between the ferromagnetic domains.

7. The element according to any of claims 2 – 4, **characterized** in that the coupling zone comprises an antiferromagnetic multiferroic layer comprising a domain wall capable of inducing said at least one pinned magnetic domain wall.
8. The element according to any of claims 2 – 7, **characterized** in that the at least one
5 magnetic domain wall is pinned on an anisotropy boundary provided into the magnetic material zone by said coupling zone.
9. The element according to any of the preceding claims, **characterized** in that the electric actuator is adapted to oscillate the pinned magnetic domain wall at a resonance frequency of the pinned magnetic domain wall.
10. The element according to any of the preceding claims, **characterized** in that the
10 electric actuator is adapted to produce an internal domain wall resonance mode, such as a local standing spin wave mode, in the oscillating pinned magnetic domain wall, at said oscillation frequency.
11. The element according to any of the preceding claims, **characterized** in that the
15 electric actuator is adapted to oscillate the pinned magnetic domain wall in a direction perpendicular to the pinned magnetic domain wall.
12. The element according to any of the preceding claims, **characterized** in that the oscillation frequency is 100 MHz – 100 GHz, in particular 1 GHz – 100 GHz.
13. The element according to any of the preceding claims, **characterized** in that the
20 oscillation frequency of the actuator is tunable.
14. The element according to any of the preceding claims, **characterized** in that the electric actuator comprises means for feeding alternating current through the at least one magnetic material zone for oscillating the at least one pinned magnetic domain wall.
15. The element according to claim 14, **characterized** in that the alternating current is
25 adapted to flow perpendicular to the at least one pinned magnetic domain wall.
16. The element according to any of the preceding claims, **characterized** in that the at least one magnetic material zone comprises a microwire or a nanowire.

17. The element according to any of the preceding claims, **characterized** in that the at least one magnetic material zone comprises at least two pinned magnetic domain walls, and the electric actuator is adapted to oscillate the at least two pinned magnetic domain walls simultaneously for emitting coherent spin waves from the at least two pinned
5 magnetic domain walls.
18. The element according to claim 17, **characterized** in that the at least two pinned magnetic domain walls are provided in different magnetic material zones.
19. The element according to claim 18, **characterized** in that the different magnetic material zones are provided in the form of microwires or nanowires parallel to each other
10 at the location of the pinned magnetic domain walls.
20. The element according to claim 17, **characterized** in that the at least two pinned magnetic domain walls are provided in a single magnetic material zone.
21. The element according to claim 20, **characterized** in that said single magnetic material zone comprises a single microwire or nanowire and that the at least two pinned magnetic
15 domain walls are provided at different longitudinal positions of the microwire or nanowire.
22. The element according to any of claims 17 – 21, **characterized** in that the at least one magnetic material zone is located adjacent to a layer comprising a domain wall capable of inducing said at least two pinned magnetic domain walls.
23. The element according to any of claims 17 – 22, **characterized** by comprising at least
20 two magnetic material zones and the electric actuator is adapted to feed alternating currents through the at least two magnetic material zones in the same phase and/or comprises means for providing a non-zero phase difference between the currents.
24. The element according to any of the preceding claims, **characterized** by comprising
- a ferroelectric layer comprising at least two ferroelectric domains separated by a
25 ferroelectric domain wall,
 - at least two magnetic material zones arranged on the ferroelectric layer as ferromagnetic microwires or nanowires crossing said ferroelectric domain wall, whereby a pinned ferromagnetic domain wall is induced to each of the wires by the ferroelectric domain wall, and

- said electric actuator being adapted to oscillate the pinned ferromagnetic domain walls with fixed phase relation so as to emit coherent spin waves therefrom.

25. The element according to any of the preceding claims, **characterized** by comprising

- a ferroelectric layer comprising at least three ferroelectric domains separated by at least two ferroelectric domain walls,
- at least one magnetic material zone arranged on the ferroelectric layer as a ferromagnetic microwire or nanowire crossing said at least two ferroelectric domain walls, whereby pinned ferromagnetic domain walls are induced to the wires by the ferroelectric domain walls, and
- said electric actuator being adapted to oscillate the pinned ferromagnetic domain walls with fixed phase relation so as to emit coherent spin waves therefrom.

26. The element according to any of the preceding claims, **characterized** in that the at least one magnetic material zone is adapted to serve as a spin wave guide carrying the spin waves emitted from the magnetic domain wall contained therein.

27. A magnonic logic component comprising

- a first magnonic element for emitting spin waves,
- at least one logic element capable of interacting with the spin waves emitted, and
- a second magnonic element for detecting the spin waves emitted by the first magnonic element,

characterized in that the first magnonic element is an element according to any of the preceding claims.

28. The logic component according to claim 27, **characterized** by being a

- magnonic transistor, or
- magnonic logic gate, such as a gate performing an AND, NAND, OR, XOR or XNOR operation, or
- a magnonic memory device, or
- a magnonic crystal,

wherein the first magnonic element forms a functional part thereof.

29. The magnonic logic component according to claim 27 or 28, **characterized** in that the first magnonic element comprises an element according to any of claims 17 – 25 and the at least one logic element is capable of interacting with at least some of said coherent spin waves in response to input of said at least one logic element, and the second magnonic
5 element is capable providing an output depending on the said interaction.

30. The magnonic logic component according to any of claims 27 – 29, **characterized** in that the component is adapted to operate according to the Mach-Zehnder principle.

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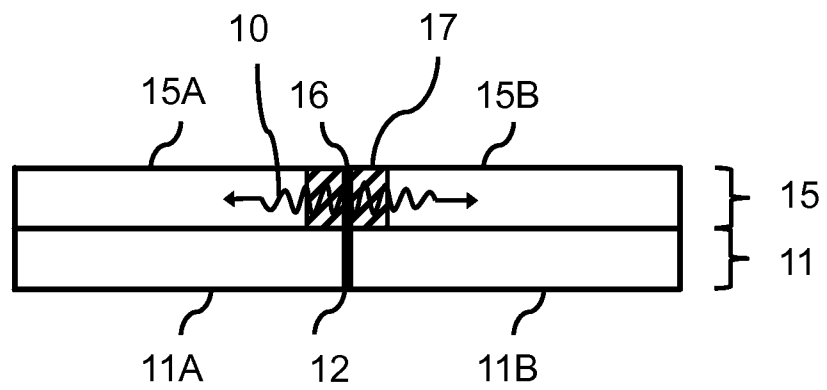


Fig. 1A

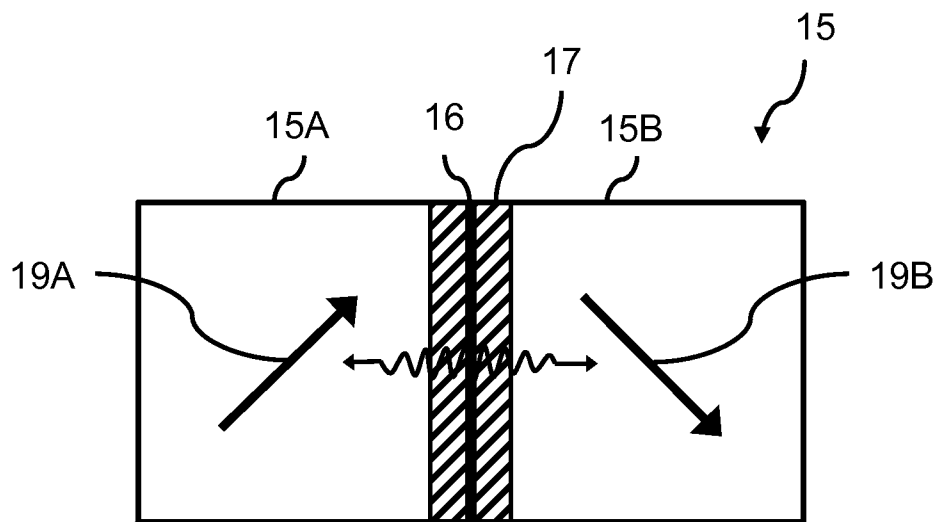


Fig. 1B

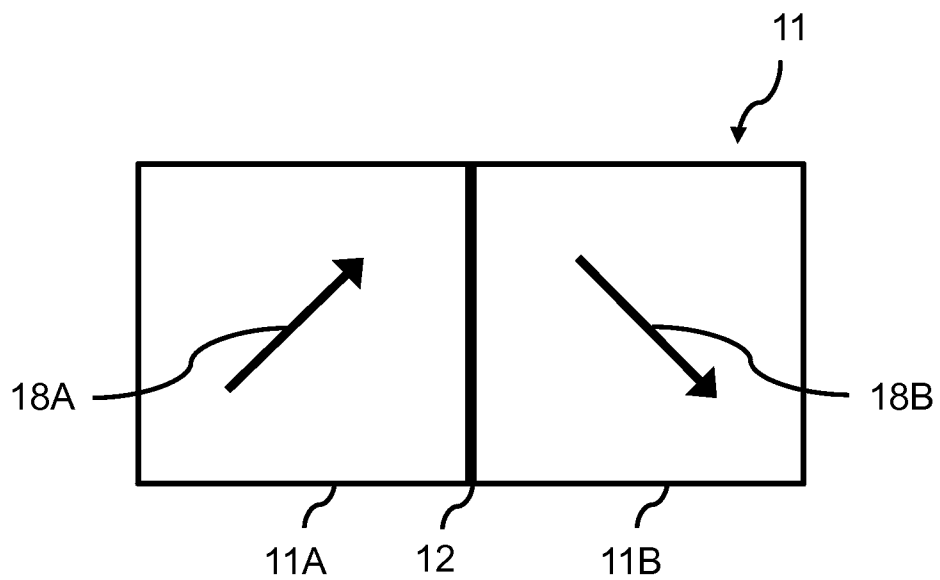


Fig. 1C

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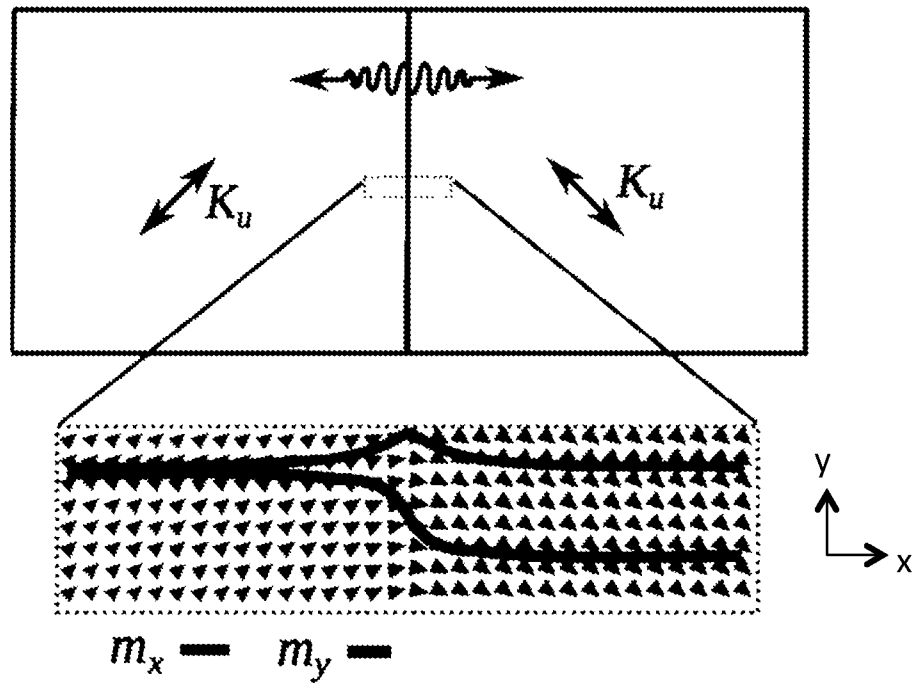


Fig. 1D

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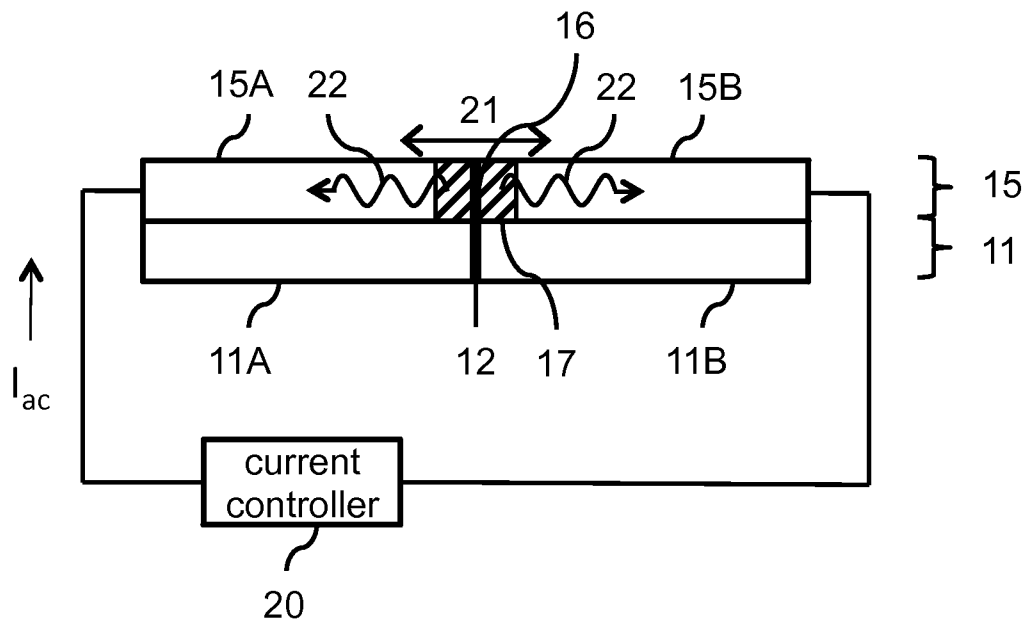


Fig. 2A

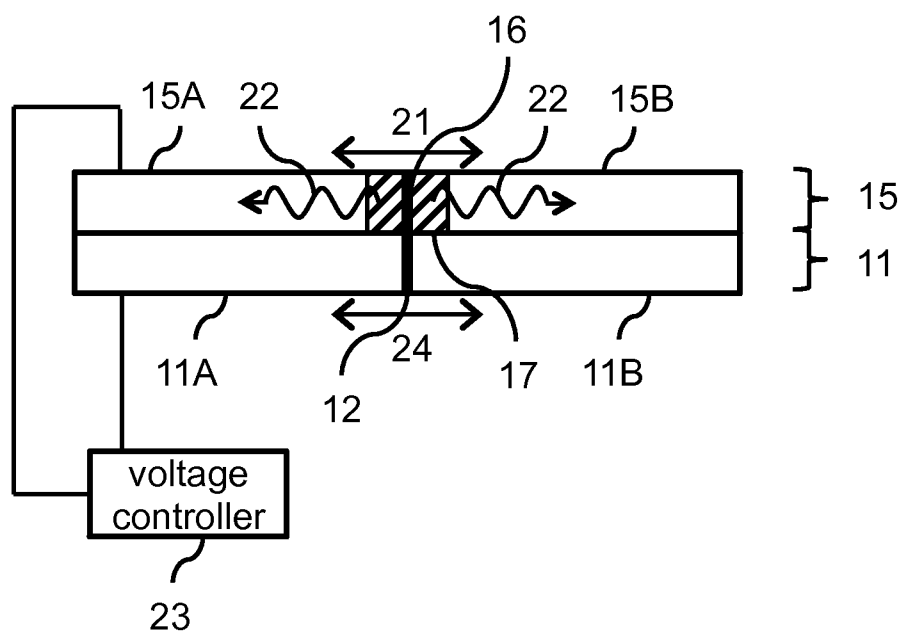


Fig. 2B

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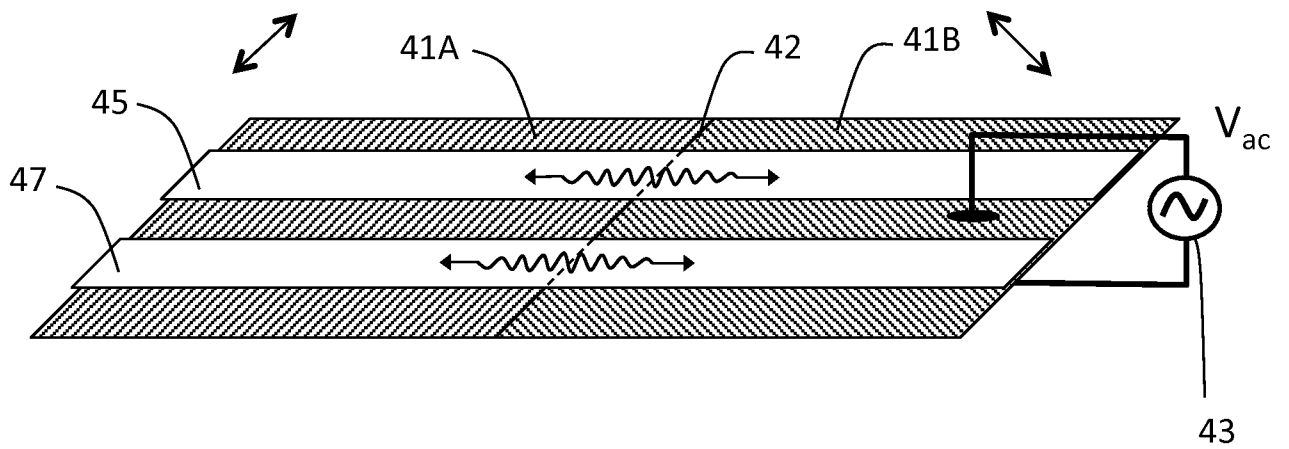
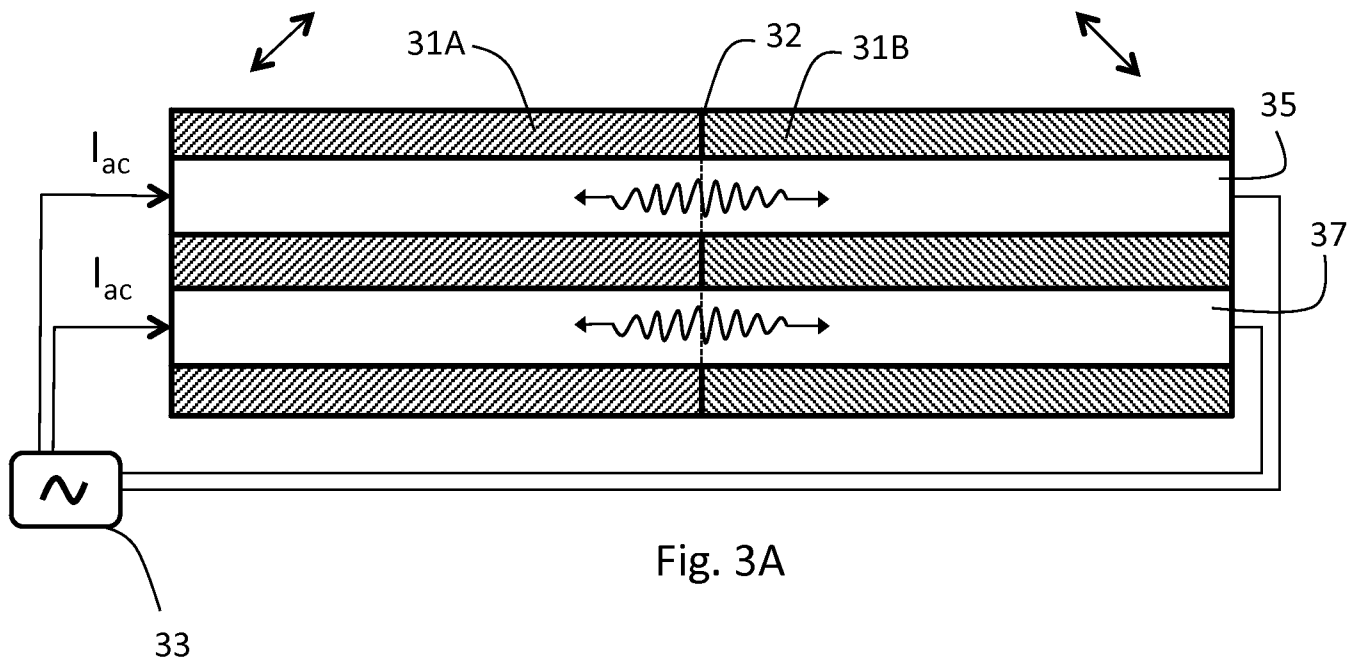


Fig. 3B

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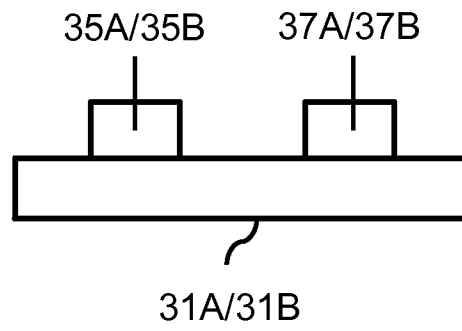


Fig. 4A

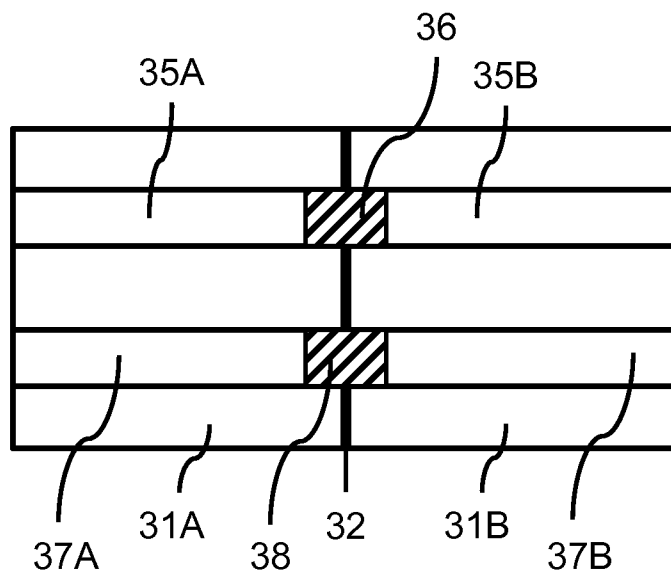


Fig. 4B

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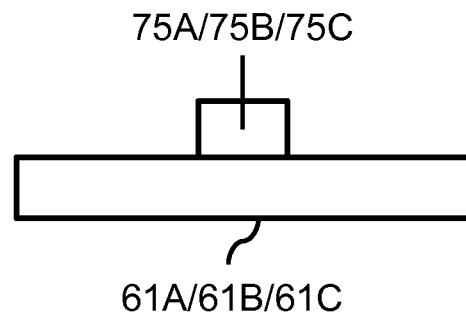


Fig. 5A

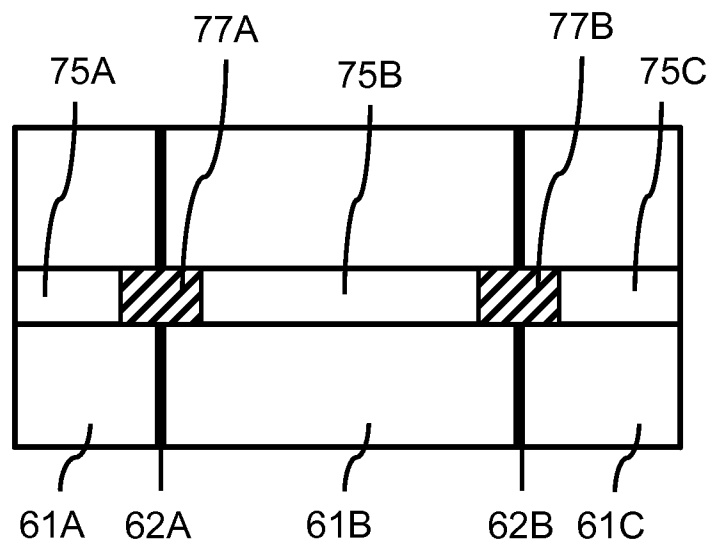


Fig. 5B

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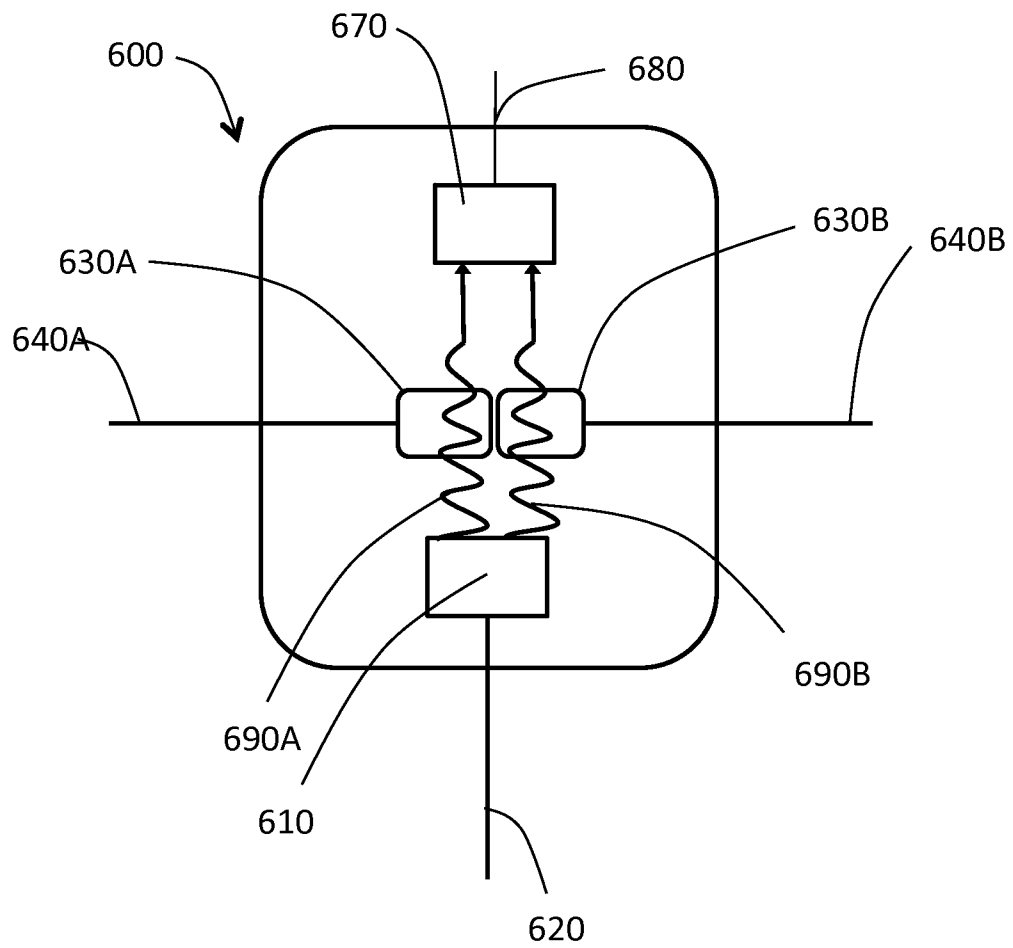


Fig. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/FI2016/050402

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L43/00 H03B15/00 H03K19/168
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L H03B H03K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MANZHOS I V: "Resonance excitation of spin waves in ferroelectric/ferromagnets by oscillations of ferroelectric domain walls in an alternating electric field", FERROELECTRICS, vol. 162, no. 1-4, 1994, pages 281-285, XP009191403, ISSN: 0015-0193 the whole document	1,9-13, 17,20,26
A	HERMSDOERFER S J ET AL: "A spin-wave frequency doubler by domain wall oscillation", APPLIED PHYSICS LETTERS, vol. 94, no. 22, 223510, 4 June 2009 (2009-06-04), XP012121538, ISSN: 0003-6951, DOI: 10.1063/1.3143225 the whole document	1-30

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

18 August 2016

Date of mailing of the international search report

29/08/2016

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Authorized officer

Köpf, Christian

INTERNATIONAL SEARCH REPORT

International application No
PCT/FI2016/050402

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2012/019806 A1 (LEIBNIZ-INSTITUT FÜR FESTKÖRPER- UND WERKSTOFFFORSCHUNG DRESDEN EV) 16 February 2012 (2012-02-16) page 7, line 19 - page 8, line 31; figures 1, 2 page 1, lines 15-20	1-30
A	----- VAN DE WIELE B ET AL: "Electric field driven magnetic domain wall motion in ferromagnetic-ferroelectric heterostructures", APPLIED PHYSICS LETTERS, vol. 104, no. 1, 012401, 2 January 2014 (2014-01-02), XP012184594, cited in the application the whole document	1-30
X,P	----- VAN DE WIELE B ET AL: "Tunable short-wavelength spin wave excitation from pinned magnetic domain walls", SCIENTIFIC REPORTS, vol. 6, 21330, 17 February 2016 (2016-02-17), XP055296014, DOI: 10.1038/srep21330 page 1, last paragraph - page 8, paragraph 1 -----	1-3,5,6, 8-30

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/FI2016/050402

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2012019806	A1	16-02-2012	NONE
