（ 続紙 １ ）

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論文題目	Three-dimensional domain wall motion memory with artificial ferromagnet (人工強磁性体を用いた三次元磁壁移動メモリの研究)		

（論文内容の要旨）

In this thesis, a new type of three-dimensional domain wall motion named vertical domain wall motion memory with artificial ferromagnet is proposed and investigated. The device is promising to solve the main problems observed in the traditional domain wall motion devices: (1) the domain wall width problem, (2) the domain wall position controllability problem, and (3) the high driving current problems. In the first research, we used the micromagnetic simulation to demonstrate the feasibility of our proposed device. According to the simulation results, we conclude that this device can solve the three major problems that traditional domain wall motion memory faced. In the second research, we further found that the high thermal stability and low current driven properties can be simultaneously achieved in our proposed device. Our proposal provides a promising way to speed up the commercialization of domain wall motion memory.

In the first research shown in chpater3 of the thesis. we propose a three-dimensional structure of domain motion memory cell, in which the vertical magnetic wire is composed of the periodically stacked bi-layers: strong coupling layer, which is named after its relatively strong magnetic exchange stiffness, and a weak coupling layer, which shows relatively weak exchange stiffness. The concept of this device is also proposed. The strong coupling layer is aimed to carry the logic bit, and the weak coupling layer is to carry domain wall. We applied the simulation on MUMAX3, a micromagnetic analysis tool, to demonstrate the feasibility of our proposed device.

Based on the simulation results, we found it possible to tune the domain wall width by the exchange stiffness of weak coupling layers. With the exchange stiffness smaller than 3 pJ/m, we can obtain the domain wall width narrower than 3 nm. Also, we can confine domain wall precisely in the weal coupling layer and achieve high domain wall position controllability. Besides, the domain wall motion can in our proposed device can be driven under the current density level of 10^{10} A/m^2. The results above suggests that our device can solve the main problems in the traditional domain wall motion devices.

In the second research shown in chapter4 of the thesis, we numerically demonstrated the current-driven properties, and the depinning field relative to the thermal stability in our device. Two major phenomenon was found in our proposed device. First, with the optimized current density and current pulse, it is possible to drive the domain wall motion while keeping the domain wall in the weak coupling layer, suggesting the position of domain wall can be precisely control. Second, by setting the Ku of strong coupling layer to around

10^6 J/m3, a two-barrier system can be observed, indicating it is possible to achieve low critical current density for domain wall motion around 10^{10} A/m^2 with high depinning field at the same time. The results suggest that, with the memory structure proposed in these studies, it is feasible to achieve narrow domain wall width, high domain wall position controllability, low driving current, as well as high thermal stability at the same time. Our studies provide a promising way to achieve low power consumption, high storage density, and high reliability domain wall motion memory easy to put into commercial production.

We further fabricated the devices of vertical domain wall motion memory proposed in the above researches, as shown in chapter5 of the thesis. We demonstrate the preliminary study of the vertical domain wall motion memory achieved by the artificial ferromagnet beginning with a tri-layer device that composed of two strong coupling layers and one weak coupling layer. We successfully nucleated the domain wall into the devices and observed the giant magnetoresistance of the devices. In the current driven switching measurement, we derived the critical current density that is needed to drive the domain wall motion (magnetic switching) in the tri-layer devices. Low critical current density down to 3.7×10^{10} A/m^2 can be observed. These results suggest it is a promising way to decrease the driving current of the device.

In chpater6 of the thesis, we performed another study in the two-dimensional domain wall motion nanowires. We investigated experimentally and numerically how the interlayer coupling affects the critical current densities for driving domain wall motion in a spin-orbit-torque-driven perpendicularly magnetized synthetic antiferromagnet system. Positive correlation was found between the interlayer couplings and the critical current densities, which can be attributed to the suppression of the azimuthal angle of the domain wall when in a synthetic antiferromagnet with strong interlayer coupling, based on the simulation results. This discovery provides us a new way to achieve low driving current in the high-speed domain wall motion devices achieved by synthetic antiferromagnet, and also provides us the methods to obtain low domain wall velocity applications in the future.

（論文審査の結果の要旨）

本論文では新しいタイプの磁壁移動メモリに関する提案と研究を行った。本論文は主に3つの部分から構成されている。第１部分および第２部分では、三次元磁壁移動メモリの提案と実現の可能性に関するシミュレーションを行い、第３部分では、人工反強磁性体を用いた2次元磁性細線についての実験とシミュレーションを行った。

第１部分「人工強磁性体を用いた低電流駆動垂直磁壁移動メモリ」では、新しいタイプの記憶素子を提案した。この記憶素子は「人工強磁性体」という多層膜で加工された強磁性体細線から構成され、一つの細線は「記録層」と「磁壁層」が周期的に積み重なった多層構造を持つ。シミュレーションの結果、提案した記憶素子は、従来デバイスの問題点であった「狭い磁壁幅」、「高い位置制御性」、および「低い駆動電流」を同時に実現することができることが明らかとなった。

第２部分「人工強磁性体を用いた垂直磁壁移動メモリにおける低駆動電流と高熱安定性」では、提案した三次元磁壁移動メモリの駆動電流と熱安定性をシミュレーションで調べた。シミュレーションの結果、提案した素子は第１部分で示した磁壁移動メモリの従来の問題点を解決できるだけでなく、低駆動電流と高熱安定性を同時に達成することもできることがわかった。

第３部分では、人工反強磁性体細線における磁性層間相互作用と磁壁駆動電流の相関を実験とシミュレーションで実証した。この結果から、強い磁性層間相互作用は磁壁の磁化方向を示す方位角を抑制することがわかった。この結果は、人工反強磁性体の磁性層間相互作用を用いた磁壁の速度制御や駆動電流制御が可能であることを示唆している

よって、本論文は博士（理学）の学位論文として価値あるものと認める。また、令和４年１月１８日、論文内容とそれに関連した事項について試問を行った結果、合格と認めた。

要旨公表可能日：　　　　　年　　　月　　　日以降