（ 続紙 1 ）

京都大学	博 士（ 理 学 ）	氏名	李 恬
論文題目	Spin wave propagation in ferromagnetic nano-structures （強磁性ナノ構造体中のスピン波輸送の研究）		

（論文内容の要旨）

Spin waves, which are the propagating disturbances in magnetic materials, have attracted great interest recently. In this thesis, two topics on spin wave propagation in nano-structures are introduced: Superior spin pumping effect via high energy magnon propagation, and Snell's law for isotropically propagating spin wave.

A new unidirectional magnetoresistance was observed in ferromagnet and heavy metal bilayers. It is suggested that it may originate from magnon generation with 2 different energy scale. To investigate the propagation of magnons, in the first topic, non-local harmonic measurements of unidirectional MR in Py(permalloy)/Pt bilayers are performed. Non-local harmonic measurements are performed by measuring 1^{st} and 2^{nd} harmonic voltage of the non-local electrodes, while applying ac current between the local electrodes. Furthermore, to better understand the propagation properties of magnon generations, non-local electrodes with different distances to the local electrodes enable a distance dependence measurement of the unidirectional magnetoresistance.

The experiment concept can be explained as follows: When a charge current flows into Py/Pt bilayer between the local electrodes, spin polarized current enters Py from Pt layer due to spin Hall effect. According to Heisenberg model, when the injected spin and the local magnetic moments of Py are antiparallel to each other, both the injected spin and the local spin are flipped. During this process magnons are generated, which are suggested to have a frequency in the THz regime. Additionally, a GHz magnetization oscillation is reported to be induced by spin transfer torque over a threshold current. Both THz and GHz magnons transfer along the wire and reach the non-local part, which results in change of non-local voltage by the following 3 scenarios; Magnons at the non-local part pump spin current into Pt layer, which are later converted into charge current by ISHE of Pt. Meanwhile, because of the existence of magnon, resistance of non-local part of wire increases due to electron-magnon scattering. Furthermore, over a threshold current, AMR and SMR observed in the wire is rapidly reduced by GHz oscillation, for the reason that they component of magnetic moments decreases.

From the experimental results, both non-local 1^{st} harmonic and 2^{nd} harmonic signals are observed. Current density dependence of non-local 2^{nd}

harmonic voltage, which originate from electron-magnon scattering, shows threshold behavior, which implying two types of magnons with different energy scales, i.e. GHz magnons and THz magnons, are involved in this process. Meanwhile, the current density dependence of 1st harmonic voltage, dominated by spin pumping, does not show clear threshold behavior, implying that although both the high energy and low energy magnons propagate to the non-local region, the high energy magnons are much more efficient for spin pumping and spin current generation.

In the second study, Snell's law for isotropically propagating spin wave, micromagnetic simulations of YIG thin film are performed to investigate the refraction properties of 2 types of isotropically propagating spin waves by utilizing a thickness step.

Spin waves originate from both exchange interaction and dipole-dipole interaction, DEFVWs, and spin waves dominated only by dipole-dipole interaction, MSFVWs are studied. It was found that both types of spin waves propagate isotropically and the Snell's law in optics can be applied in the present system, which provide a simple design of magnonic devices. It is also found that Snell's law for these two types of isotropic spin waves are found to have different behaviors: with MSFVW, refraction angle is independent of the resonant frequency it depends on the resonant frequency, while in the case of DEFVW, suggesting that the chromatic aberration effect should be taken into account in designing magnonic devices using spin waves with high wavenumbers.

Spin waves have attracted magnificent interest as a novel technology that have huge potential to be applicated as data transport medias, logic devices, etc. The performance of the devices based on data transport mostly relies on the conversion efficiency between propagating magnons and spin current, while the designable propagation properties are crucial for logical devices.

Researches introduced in this thesis unveils spin wave propagation phenomena in ferromagnetic nano-structures and suggests new possibilities of spin wave devices.

（続紙　２　）

（論文審査の結果の要旨）

本論文は、強磁性ナノ構造体中のスピン波輸送について研究したもので、「高エネルギーマグノン輸送による効率的スピンポンピング効果」及び「スピン波の屈折現象についての研究」の2つの内容で構成されている。

近年、強磁性金属/非磁性重金属の二層膜において、電流によってギガヘルツとテラヘルツの周波数を持つ2種類のマグノンが励起されることを示唆する新たな磁気抵抗効果が観測された。そこで、本研究では、電流によって励起されたマグノンの伝播特性を調査した。電流によって局所的に励起されたマグノンが強磁性体中を伝搬する過程を、逆スピンホール効果による電圧変化および電子マグノン散乱による抵抗変化を利用して、電気的に検出した。検出距離を変えることで、2種類のマグノンの減衰を観測することに成功した。さらに、ギガヘルツマグノンとテラヘルツマグノンによるスピンポンピングの強度と比べると、テラヘルツマグノンが生成するスピン流がギガヘルツマグノンより大きいことがわかった。

「スピン波の屈折現象についての研究」では、マイクロマグネティックシミュレーションを用いて、双極子相互作用および交換相互作用を考慮した等方的スピン波のスネルの法則を調査した。双極子相互作用のみ考慮した静磁前進波と双極子相互作用と交換相互作用両方考慮したスピン波（dipole-exchangeスピン波）ともに、スピン波はネルの法則に従うことがわかった。しかし、dipole-exchangeスピン波は屈折率がスピン波の周波数に依存することが明らかとなり、dipole-exchangeスピン波を利用したスピン波素子の設計では色収差を考慮することが必要であることがわかった。

本学位論文で示された二つの研究結果は、スピン波の基礎物性を明らかにし、応用利用に対する重要な知見も与えている。

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3年1月19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