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論　文　内　容　要　旨

(NO.　1)

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学位論文の題　　目	Vortex rectification effect in a weak-pinning superconducting alloy Mo-Ge （弱ピンニング超伝導合金 Mo-Ge におけるボルテックス整流効果）		

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Rectification refers to the generation of a d.c. output from an a.c. input, and is characterized by an asymmetric transport of carriers in response to a d.c. driving force. A typical example of a rectifier would be a semiconductor diode, which is realized by a p-n junction, where the electrical resistivity ρdepends on the direction of charge current I, that is, $\rho(I) \neq \rho (- I)$. Such devices are of interest from technological perspective, especially in energy harvesting. Due to the short coherence length of electrons in condensed matter, the requirement for asymmetric electric transport is that of a spatially asymmetric potential on atomic scale, which can be realized by an artificial junction, or by lowered crystalline symmetry.

The purpose of the present thesis is to extend the concept of rectification to carriers with long coherence length by experimentally demonstrating a vortex rectification effect in a superconductor without lowered crystalline symmetry. For carriers with a propagation length longer than the specimen size, an asymmetry in transport can be generated by placing a bulk specimen without lowered crystalline symmetry into an asymmetric external environment. The asymmetry at the boundaries of the specimen translates into an asymmetry of carrier transport in the bulk with respect to the direction of flow. A vortex in a type-II superconductor is a prototype of a carrier with long coherence length. A vortex is a topological soliton in the phase of the superconducting order parameter, and can be created or annihilated only at the superconductor boundaries. Therefore, vortex flow is a conserved quantity in the bulk. Notably, in weak-pinning superconductors, vortex flow can be totally governed by the nucleation energy barrier at the surfaces of the superconductor. This enables the realization of a vortex rectification effect based on an asymmetry between superconductor surfaces. In the present thesis, a vortex rectification effect in a weak-pinning superconductor without lowered crystalline symmetry placed in an asymmetric external environment is experimentally demonstrated and a theoretical model for rectified vortex flow is presented.

This thesis consists of 5 chapters and is organized in the following manner.

Chapter 1 contains the background and purpose of the present research, followed by a short summary of the Ginzburg-Landau (GL) description of superconductivity and of the vortex state in type-II superconductors, as well as transport properties of superconducting vortex.

Chapter 2 explains the preparation and characterization of samples as well as the measurement methods. Physical properties of Mo-Ge, a weak-pinning superconducting alloy, and $Y_3Fe_5O_{12}$ (YIG), a ferrimagnetic insulator used in this study, are also overviewed in this chapter.

Chapter 3 presents a systematic study of vortex rectification in the vortex liquid phase of Mo-Ge. In the class of amorphous type-II superconductors to which Mo-Ge belongs, thermal fluctuations in the vortex liquid smear out the pinning by the uniform microscopic disorder, making vortex motion in the vortex liquid phase essentially pinning-free. This chapter presents a study of electric transport in the vortex liquid phase of the superconductor Mo-Ge with a ferrimagnetic insulator YIG attached to one face of the superconducting film. By means of second-harmonic voltage measurements it is demonstrated that a nonreciprocal electrical resistivity appears in the vortex liquid in the presence of a ferrimagnetic YIG substrate. Generation of d.c. voltages from environmental current noise present in the measurement system is experimentally confirmed in the vortex liquid, which is consistent with the nonreciprocal electrical resistivity. A possible mechanism for nonreciprocal electrical resistivity and rectification of current noise is discussed based on GL description of superconductivity. Based on

the presented model, an asymmetry in the vortex nucleation energy at the interfaces of the superconductor with the YIG and with the vacuum is expected, which leads to an asymmetry in vortex flow in opposing directions perpendicular to the film plane. The experimental results along with the rectification model provide a comprehensive demonstration of rectification of free vortex flow in an isotropic material with asymmetric boundary conditions. This is different from the usual concept of vortex ratchets where the mean free path of a vortex is governed by a patterned periodic pinning potential. The results highlight the possibility to realize nonreciprocal electrical transport and rectification based on asymmetric external environment in other bulk systems with topological solitons, such as skyrmions in chiral magnets.

Chapter 4 is devoted to a discussion of the experimental observation of a vortex Nernst effect in Mo-Ge films. The existing work on vortex Nernst effect focuses on bulk superconductors, or on films with in-plane temperature gradients, where the vortex can be regarded as a two dimensional object. In this chapter it is demonstrated that a clear vortex Nernst effect is observed in the vortex liquid even with a temperature gradient perpendicular to the film plane. Contrary to the expectation based on the geometry of a Nernst effect, the angular dependence shows a suppression of the Nernst response for magnetic fields parallel to the film plane, which is interpreted as a signature of suppressed vortex entropy at increased magnetic fields. These results show that conventional description can be used for vortex flow perpendicular to the film plane in a vortex liquid of a weak-pinning isotropic superconductor.

Chapter 5 summarizes the results obtained in the present thesis.

The results obtained in this study demonstrate a novel rectification mechanism of carriers with long-range propagation based on asymmetric boundary conditions for pinning-free vortices in a type-II superconductor. The physical mechanism can be expected to be common to other topological solitons, such as skyrmions in chiral magnets. Such rectification mechanism may open new directions in energy harvesting or sensing of electromagnetic waves.

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論文審査の結果の要旨

超伝導ボルテックスは超伝導秩序パラメータのトポロジカル欠陥であり、その消滅・生成は超伝導体表面に限られる。この性質はトポロジカル保護と呼ばれ、ボルテックスの運動は磁気モーメントと角運動量を長距離にわたって輸送することができる。一般に、ボルテックス系の空間反転対称性を破ったとき、超伝導体は非相反な電磁応答を示すことができる。これまでに、反転対称性を持たない結晶構造を持つ超伝導体や非対称微小パターニングをした超伝導体薄膜を用いた研究が行われてきた。本研究は、ボルテックス液体相を示す超伝導体薄膜に磁性絶縁体を接触させることで、超伝導体の境界条件対称性を面間で破った系 MoGe 薄膜/イットリウム鉄ガーネット（YIG）を用いて超伝導ボルテックスの非相反輸送物性を系統的に明らかにすることを目的としている。

本系は、超伝導体 MoGe 内部の結晶空間反転対称性が破れていない系である。それにもかかわらず、MoGe/YIG 二重膜系において測定された輸送物性はボルテックス液体相で明確な非相反性を示し、ボルテックス液体相境界で急峻な非相反信号の変化がみられた。ボルテックス数のトポロジカル保護により、超伝導体 MoGe 薄膜内部のボルテックスダイナミクスは薄膜層境界（薄膜表面及び磁性体 YIG との界面）の非対称性を敏感に感じることができる。これにより非相反輸送物性が発現していることを、ボルテックス界面核生成モデルを用いて示した。更に驚くべきことに、この非相反性の発現領域では、試料測定室に入れた試料からは、自発的に電圧が発生していることを見出した。この電圧は、ボルテックス液体相境界で急峻な立ち上がりを示し、外部に負荷抵抗を繋げることで連続的に仕事を取り出せることがわかった。磁場角度依存性、外部から印加した温度勾配依存性を系統的に測定することで、この自発的電圧はボルテックス液体相で現れる非相反輸送特性が試料測定室内の微弱な電磁ゆらぎを整流することで発生していると結論した。

Jana Lustikova 氏提出の論文は、超伝導体におけるトポロジカル保護されたボルテックスがもたらす非相反現象を開拓し、超伝導体/磁性体界面における基礎物性物理分野を切り拓くものであり、高く評価できる。この成果は、提出者の Jana Lustikova 氏が高度の学識と自立して研究する能力があることを示すと判定される。よって、博士（理学）の学位論文として合格と認める。