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論　文　名	「**VORTEX DISTRIBUTION IN NANOSTRUCTURED SUPERCONDUCTING $Mo_{80}Ge_{20}$ FILMS STUDIED BY SCANNING SQUID MICROSCOPY** (走査型SQUID顕微鏡による超伝導ナノ構造$Mo_{80}Ge_{20}$薄膜の磁束量子分布の研究)」
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論文要旨

Vortex in superconductors exhibits a rich variety of phenomena. For instance, a vortex can interact with transport currents, temperature gradients, sample surfaces, defects and other vortices. An understanding of vortex states as well as vortex dynamics is one of the most important issues when considering practical applications of superconductors. While magnetization and transport properties are useful for clarifying the basic phenomenology of vortex states, they only give information on global (macroscopic) properties, and they do not provide details on local (microscopic) vortex states. Our studies in recent years have focused on understanding vortex states in specific samples such as circular and pentagonal plates by the direct visualization of vortex states using a scanning superconducting quantum interference device (SQUID) microscope. A SQUID is a very sensitive instrument for mapping out tiny current flows or magnetic moments without damaging the sample. Owing to the weak pinning nature of the amorphous $Mo_{80}Ge_{20}$ films developed in this study, vortices are able to form geometry-induced exotic configurations due to confinement of the sample geometry.

A novel principle of superconducting memory has been proposed, that is based on the use of a two-dimensional array or a network of strongly pinning sites in which information bits of “1” and “0” are indicated by the presence and absence of vortices at a pinning site, respectively. There have been many efforts to clarify vortex states in such systems. The transport properties often provide general information on the field distributions and mechanisms of flux motion in superconducting networks or

arrays. However, since these explanations of vortex states are still controversial, we carried out systematic studies on vortex states in $Mo_{80}Ge_{20}$ superconducting networks using the scanning SQUID microscope.

In what follows, we explain the contents of this thesis by summarizing each chapter.

Chapter 1 gives a brief introduction to superconductivity and describes preceding studies on vortex states in restricted geometries such as circular disks, triangles, squares and networks. We present the first theoretical prediction for investigating vortex states of nano-size pentagons on the basis of the Ginzburg-Landau theory. By comparing the free energy of locally stable states, we observed the most stable state evolving with the magnetic field. The obtained results show that penetrating vortices tend to adapt to the symmetry of the pentagon as expected from the sample geometry. The theoretical results are very suggestive of the necessity of experimental studies for comparison.

Chapter 2 describes the experimental techniques used for sample preparation and structural characterization as well as to measure the superconducting transition temperature T_c and the upper 3 critical field H_{c2}. We summarize the operation of our scanning SQUID microscope (SSM) for direct observations of vortex states. Furthermore, we discuss a novel method for improving the spatial resolution of SSM with the aid of the inverse Fourier transform, which fully takes into account the details of the pickup (sensor) coil. The spatial resolution of SSM can be enhanced up to 2 μm beyond the limitation of the pick-up coil diameter (10 μm).

Chapter 3 is devoted to characterization of samples. It was revealed that the amorphous nature of the $Mo_{80}Ge_{20}$ film could be ensured as the temperature of substrate is cooled during film deposition. The critical current J_c estimated using a magneto-optical imaging technique also confirmed that the J_c of the cooled sample is lower compared to the sample prepared without cooling. Resistivity measurements revealed that the phase transition temperature of $Mo_{80}Ge_{20}$ is 7.3 K, which is higher than in previous studies due to the higher content of Mo in our sample. The coherence length $\xi(0)$ of approximately 5 nm, estimated from the upper critical field, is consistent with previous reports on the amorphous MoGe superconductor.

Chapter 4 describes the main results on various vortex states in specific samples such as the disk and pentagon using the scanning SQUID microscope. Systematic measurements allow us to reveal how vortices are confined in a restricted sample as well as how the vortex arrangement evolves with increasing applied magnetic field. We investigated four different samples: **(1)** In a $Mo_{80}Ge_{20}$ circular disk with 90-μm diameter, we found that as the number of vortices increases up to L=5, vortices form a single-shell configuration with respect to the center. The second-shell formation starts for L=6 in the form of one vortex at the center and others in the outer shell. Furthermore, we observed six vortices forming a one-shell structure, which is very exotic, and has not been previously reported in the literature. For each vorticity, the size of a single shell decreased with increasing field due to the influence of the screening current on the vortex configuration. This means that the vortex configurations are dominantly influenced by geometrical confinement due to screening current flowing along the sample edge. For a vorticity of two, we observed a rotational degree of freedom in the vortex configuration due to the infinite symmetry of the circular disk. The observed vortex images are improved by applying a novel method for image restoration. The results clarified that our method reinforces the usefulness of the SQUID microscope remarkably for studying superconductivity on the mesoscopic scale. **(2)** For a small pentagon with a circumradius *r* of 35 μm, the vortex configuration evolves with increasing applied magnetic field as follows: starting from the Meissner state without a vortex, one vortex locates at the center, then two vortices prefer to occupy one of the five symmetric axes of the pentagon. The observed results show that the vortex pair in the pentagon has a rotational degree of five in vortex configuration as expected from the sample geometry. With further increase in the field, the vortices form a triangular, a square, and a pentagonal like vortex pattern. It is interesting to note that the vortices form a square pattern, in which two of them are symmetric with respect to a centerline of the pentagon. In other words, the vortex configuration has mirror symmetry with respect to the middle axis of the pentagon. When 4 vorticity increases from five to six, one vortex becomes located at the center of the pentagon and consequently forms a two-shell structure (1,5). The two-shell configuration still remains for a vorticity of 7, wherein the newly generated vortex is added to the outer shell to form a (1,6) configuration. In comparison between the vorticity *L* and the normalized magnetic flux Φ_p/Φ_0, we found that there is a difference between *L* and Φ_p/Φ_0 due to the external field demagnetization effect and the presence of a large screening current flowing along the sample edge. According to the observed symmetric vortex configuration, the vortex distribution was likely to be accommodated by choosing one of the five symmetric axes of the pentagon for satisfying the confinement geometry. The rules for filling the vortex shell and the existence of a magic number for a small pentagon are in good agreement with our theoretical predictions on the basis of the Ginzburg-Landau theory. **(3)** For a larger pentagon with *r*=50 μm, six vortices form just one shell structure in contrast to a small pentagon wherein the second shell formation begins for *L*=6. We observed the two-shell configuration for a vorticity of 7. This two-shell configuration of the vortex remains for *L*=8. The inner shell begins to grow at *L*=9 to form a configuration of (2,7) and (2,8) for *L*=10. We also observed two different configurations of (2,9) and (3,8) for a vorticity of *L*=11. Theoretical considerations indicate the configuration (3,8) to be the ground state for vortices while the configuration (2,9) is found to be a metastable state. **(4)** We also investigated the influence of a pinning site on the vortex configuration in the pentagon with *r*=35 μm. We found that the shell filling rules were modified in the presence of a pinning-centered site so as to accommodate vortices on a symmetry axis containing the pinning site.

Chapter 5 gives the results of the vortex distribution in a superconducting network and the procedure of doping vortices into the network when we increase the applied field in a stepwise manner. The vortices penetrate into networks following the Bean-like critical model, where the vortices enter the network from the edges and gradually reach the center with increasing field. It is interesting to note that the vortices do not move smoothly to the center but rather they hop from one cell to another due to the existence of a Meissner current in the inner part of the network. We also observed a different configuration as the system was cooled to below the critical temperature. In particular, we observed a diagonal vortex array and an isolated vortex as the system was cooled to intermediate temperatures and lower temperatures, respectively. The observed results show that vortex distribution was strongly modified due not only to the applied magnetic field but also to the temperature.

Chapter 6 presents a summary of the thesis and emphasizes important achievements. We also discuss possible future applications of the present work.

審査結果の要旨

本論文は、磁束量子のピン止めの極めて小さな超伝導ナノ構造アモルファス$Mo_{80}Ge_{20}$薄膜を開発し、その微細加工で作製した微小試料を用いて、磁束量子の特異な振る舞いを SQUID 顕微鏡を用いた観測実験と Ginzburg-Landau 理論による計算から調べ、以下の成果を挙げている。

（１）DC スパッタリング法で、アモルファス$Mo_{80}Ge_{20}$膜を作製し、磁束量子のピン止め効果の小さな試料を作製できる条件を調べ、基板冷却により金属 Mo 粒子の析出を押さえることが重要であると見出した。

（２）超伝導 $Mo_{80}Ge_{20}$ 円板を用いて、磁束量子のシェル構造や二重シェル構造を見いだし、微小円板への磁束量子の充填の法則を見出している。

（３）超伝導 $Mo_{80}Ge_{20}$ 正五角形板を用いて、磁束量子のシェル構造や二重シェル構造が、常に正五角形の対称軸を磁束量子配置の対称軸とすることを観測し、理論計算も実施して良い一致を見出した。

（４）超伝導 $Mo_{80}Ge_{20}$ 正五角形板の中心に磁束ピン止め中心を有する試料を作製して、中心に必ず磁束量子を配置することを観測し、理論計算も実施して良い一致を見出した。

（５）超伝導 $Mo_{80}Ge_{20}$ ネットワークの磁束量子配置を観測し、理論計算と定性的に良い一致を見出した。

以上の成果は、磁束ピン止め効果の弱い試料を開発したことにより、この材料を用いた超伝導デバイスの開発に貢献すると考えられ、今後のこの分野の発展に資するところ大である。