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論　文　名	「*de facto* Mesoscopic Superconducting Vortices Revealed by Scanning SQUID Microscopy」 （走査型SQUID顕微鏡によるメゾ構造超伝導体の渦糸状態の研究）
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論文要旨

Vortex penetration in type II superconductivity exhibits a rich variety phenomena and potential applications. Especially, studies to elucidate vortex states and vortex dynamics would be the most important issues in order to consider practical applications. Our studies introduce a pinning center in a star-shaped pattern as well as a sectoral defect in a Pacman-shaped plate. We are able to induce the symmetry breaking in a superconductor disk with infinite degrees of freedom in symmetries. We found good agreements between theoretical predictions and experimental images of vortices in various different mesoscopic shapes of $Mo_{80}Ge_{20}$ thin films observed by using a scanning SQUID microscope. We are able to regard our sample as being mesoscopic even if an actual size is in the scale of micrometer because the penetration depth is extremely elongated in our very thin film. This makes it possible to treat our sample as a *de facto* mesoscopic superconductor because physics involved is identical with that in a real mesoscopic superconducting system.

Besides, we plan to construct new vector scanning SQUID microscopy to achieve the high sensitivity and the high spatial resolution by using our vector SQUID sensor.

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

Chapter 1 provides a brief introduction to the history and basic properties of superconductivity. We also present the fundamental theoretical framework for describing the phenomenological properties of superconductivity such as the London theory and the Ginzburg-Landau theory. We would like to give the basic concepts of superconducting Josephson junction and SQUID sensor.

Chapter 2 presents the novel vortex states on a regular concave decagon as a *de facto* mesoscopic system, which were investigated not only by theoretical GL calculations but also by experimental studies with a scanning SQUID microscope. We succeeded in fabricating highly-homogeneous amorphousness $Mo_{80}Ge_{20}$ films. According to our systematic studies on characteristic features of mesoscopic superconductors, we summarize: **(1)** The vortex distribution in a star plate tends to share one of five symmetric axes with that of the star geometry. **(2)** We revealed that a single-shell configuration appears at around the geometrical center until the vorticity increases up to L=5. **(3)** The appearance of inner vortices elucidated the geometrical influence of the vortex pattern by pushing outer vortices toward the surrounding regime of the star so as to occupy the inside of five vertices. **(4)** In order to create novel vortex configurations, we intentionally introduced an artificial pin at the center of the star plate. The vortex pinned at the artificial defect forces its neighbors to sit in the vertex areas until five vertices are fully occupied by five vortices. This will cause two different distributions on vortex configuration with the same vorticity $L = (1, 2, 5)$. We found that an artificial pin was combined with a vortex or a corner boundary to work as a gate hinder for vortices for allowing other vertex under the interaction of adjacent vortices. The results show that we succeeded in obtaining novel vortex states in the star-shaped pattern by introducing an artificial pin at the center.

Chapter 3 describes that a sector defect causes the geometrical symmetry breaking in a superconductor disk with infinite degrees of freedom regarding symmetry. Therefore, we observed the vortex distribution with interesting features as follows: **(1)** The vortex configuration is modified clearly from *a well-known shell structure* of the circle plate to *an exotic arc structure* of the Pacman-shaped plate. **(2)** The vortex configuration always prefers to share a unique symmetry line with the bisector line of the defect. **(3)** By alternating the opening angle of sectoral defect, we discovered the existence of *the magic number* in the vortex configuration of the Pacman geometry. However, it is quite interesting to note that the transient stage to multi arcs in the Pacman pattern can easily be controlled by tuning an opening angle of the sectoral defect. **(4)** By comparing the free energies of vortex distributions, we found that the multiple metastable vortex states will appear at the same vorticity when the ratio of the outer-arc vorticity to the inner-arc vorticity becomes approximately two. **(5)** To confirm the predictions from the GL calculations, we systematically observed the vortex configuration in a $Mo_{80}Ge_{20}$ Pacman thin film pattern of 85-μm diameter and an opening angle of 30 degrees by using the scanning SQUID microscope. The weak pin occasionally happened in a superconductor so that vortices cannot take a symmetric configuration with sharing the same symmetry line with the Pacman pattern. .

Chapter 4 presents the details of our proposition to design how to fabricate a vector SQUID sensor. **(1)** The parameters of vector SQUID sensor are optimized to achieve the high sensitivity and the preferential noise characteristics by considering the sensor parameters as the screening parameter $b_{\mathrm{L}}=1$ and the Stewart-McCumber parameter $b_{\mathrm{c}} = 0.7$. **(2)** The standard fabrication process is able to fabricate by a minimal area of Josephson junction of 2x2 μm^2 and the critical current $I_0$of a JJ about 12.5μA which is suitable to improve a loop inductance, and it is necessary to keep the relation $b_{\mathrm{L}}=1$ and the condition of $\Gamma \equiv 0.0138 << 1$ at 4 K. **(3)** We succeeded in fabricating the vector sensor on a chip size of 2.9 mm x 2.9 mm, where three vector pick-up coils are located at a corner of the chip. **(4)** The positions of vector pickup coils were designed to align along a parallel single line to the sample surface in order to keep the three pickup coils at the same height from the surface during scanning. **(5)** The height of the vector pickup coil with respect to sample surface is reduced as small as possible by polishing the corner of the silicon chip of an as-prepared distance of 70μm from the tip to the *Z*-coil center. **(6)** In order to improve the sensitivity of each sensor, the vector SQUID sensor is equipped with a double winding structure, of which the effect was confirmed by our experiments by comparing with a single coil SQUID sensor. **(7)** The inductance of the *Z* pickup coil was fabricated as 20 pH while the inductances of the *X* pickup coil and the *Y* pickup coil were limited to 10 pH by the thickness and the number of Nb and SiO_2 layers. **(8)** The vector pickup coil system is connected directly to a washer where two JJs are placed with a stripline fully covered by a Nb thin film. **(9)** In order to investigate the characteristics of each vector SQUID sensor, we constructed the measurement system by paying careful attentions to reduce the noises. The measurement system is fully controlled to operate properly by a LabVIEW program. **(10)** We were therefore able to measure the characteristics of the different SQUID sensors rather systematically such as the I-V curves, and used to estimate a critical current of the SQUID sensor as $I_{\mathrm{c}} = 27\ \mu A$. All of the inductances of the SQUID sensor were determined by analyzing the periodic oscillations of the V-Φ curves of the testing chip with changing a current applied to each inductance. **(11)** The V-Φ characteristics of a vector SQUID sensor show a clear oscillation as a function of an external magnetic field under various different bias currents. **(12)** The V-$\Phi(I_{\mathrm{b}})$ curve indicates that we succeeded in cancelling the *LC* resonance of our sensor although it is the basic requirements to capture a vector magnetic field over a wider range of bias currents tunable by a FLL readout circuit.

Chapter 5 describes the construction of a vector scanning SQUID system. **(1)** We finished to draw every detailed designs of the vector scanning SQUID system by using a CAD software, and all the parts were machined by our university workshop. **(2)** We interface successfully our vector SQUID sensor with a 3-channel SQUID readout circuit. This is an important task to construct the scanning vector SQUID microscope by ourselves. **(3)** We use a Gifford-McMahon cryocooler of the cooling power of 1 W at 4 K which is able to cool a minimal temperature down to 3.5 K for conducting long-time systematic measurements. **(4)** We scan the coils in the 2D Cartesian coordinate in a step to improve the spatial resolution of vector magnetic field images by using an *XYZ* piezo-driven scanner with a high spatial resolution of 10 nm. **(5)** We use a temperature controller to control the temperatures of sample and sensor. **(6)** To ensure for maintaining the 6-MHz bandwidth and for reducing a disturbance from environment noises, the electrical leads from the vector SQUID sensor are fed into a vacuum connector at room temperature through Beryllium Copper Loom cables. **(7)** The first testing of our vector scanning SQUID microscope is obtained by placing a tiny field coil on the sample holder to produce a magnetic field to the vector pickup coils at around the center of the coil. We succeeded in measuring the periodic characteristics of the V-Φ characteristics with increasing the applied magnetic field. **(8)** Before completing to construct a new vector SQUID microscope, we meantime used the platform of a commercial scanning SQUID sensor to test our new SQUID sensors. **(9)** In analyzing of three componential magnetic field images, we found that the diamagnetic Meissner effect in *X*, *Y* and *Z* coil influences to each other to modify the original profile of magnetic field. **(10)** A remaining step to construct the system would include the wiring of the SQUID sensor, the readout circuit, the *XYZ* stages, and the temperature controlling system. We also need a controlling program and an image processing software to treat the magnetic field profile obtained by scanning SQUID microscopy.

Chapter 6 gives conclusions of the thesis, and we emphasize the importance of our achievements. We also discuss possible future applications of the present work.

審査結果の要旨

本論文は、磁束ピン止めの効果が小さなアモルファス MoGe 薄膜で、磁束侵入長がバルク物性値と比べて非常に長くできるため、SQUID 顕微鏡で計測できるサイズでも、物理としてはメゾ構造超伝導体と見なした物性研究が可能となる工夫をしている。微細加工で作製した星形とパックマン形の超伝導微小板試料に対して、量子磁束の特異な振る舞いを実験と理論から調べた。また、磁場ベクトルを測定できる走査型 SQUID 顕微鏡の開発を行い、以下の成果を挙げている。

（１）星形の超伝導 $Mo_{80}Ge_{20}$ 微小板を用いて、量子磁束の殻構造と充填の法則を調べて、ギンンツブルク・ランダウ方程式を使った理論計算と系統的に比較して、よい一致を得た。

（２）パックマン形の超伝導 $Mo_{80}Ge_{20}$ 微小板を用いて、量子磁束（渦糸）の殻構造と充填の法則を調べ

て、これまで知られていなかったアーク形磁束配列構造を初めて見いだした。また、ギンンツブルク・ランダウ方程式を使った理論計算でも追認して、微小板の空間対称性を破ることがエキゾチックな量子磁束状態の発見に繋がると実証した。

（３）磁場ベクトル測定ができるSQUID素子を設計・製作し、量子磁束による磁場のX成分、Y成分、Z成分を実測する、世界初の成果を挙げている。

以上の成果は、超伝導微小系の物性を明らかにしたことで超伝導デバイスの開発に貢献すると考えられ、開発した装置も今後、幅広い研究分野の発展に資するところが大である。