High-Q Vibrating Wire for the Study of Quantized Vortices in Superfluid ^{3}He

Yuka Hayashi, Hisashi Nakagawa, Hideo Yano [1], Osamu Ishikawa, Tohru Hata

Graduate School of Science, Osaka City University, Osaka 558-8585, Japan

Abstract

To investigate quantized vortices in superfluid ^{3}He we have fabricated a vibrating wire from single crystal silicon with low impurities. The wire is controlled in a goal post shape of 2 mm square. We have investigated the characteristics of the vibrating wire. The obtained quality factor (Q) is 1.2×10^5 at the resonant frequency of 8.7 kHz. The high-Q and shape-controllable vibrating wire of a single crystal silicon has the advantage for the creation and detection of the quantized vortices in superfluid helium.

Key words: quantized vortex; superfluid helium3; vibrating wire; silicon sensor

1. Introduction

Recently quantized vortices and turbulences in superfluid ^{3}He and ^{4}He in the ballistic regime have been studied with oscillators such as an oscillating micro sphere[1], an oscillating grid[2], and a vibrating wire[3,4]. Although the oscillators create the vortices in superfluid actually, the mechanism of the vortex creation has not been clarified yet. We have developed a new oscillator fabricated from silicon for studying the quantized vortex creation in superfluid ^{3}He.

So far conventional Nb-Ti vibrating wires have been used for the quantized vortex study in superfluid ^{3}He [3,4]. Our oscillator is also a kind of the vibrating wire and is fabricated from single crystal silicon wafer. Single crystal silicon is useful for high-Q oscillators [5] and oscillator shape can be easily controlled by etching [6]. These characteristics are advantages of the vortex creation study. In the present paper we will report the characteristics of the silicon vibrating wire.

2. Fabrication and Experimental Method

The vibrating wire was fabricated from a 500 μm thick $\langle 100\rangle$ silicon wafer with boron doping of 0.5$\sim$100 $\Omega\cdot$cm. Gold was evaporated into etching patterns of a goalpost shape on an upper side of the wafer and a 5mm$\times$5mm open square on the other side. The wafer was etched using a solution of potassium hydrate. Finally we obtained the vibrating wire which is composed of silicon wire of 100μm wide and controlled into a goal post shape of 2mm$\times$2mm as shown in Fig. 1. The evaporated gold can be also utilized for an electric lead.

The present wire is similar to a silicon vibrating wire studied by Grenoble group [7]. They fabricated the wire by a reactive ion etching (RIE), while we used only the chemical etching with KOH. The chemical etching utilizes different etching speeds in different crystal orientations for a shape control. One can therefore obtain a crystal facet after the chemical etching. As a result the wire surface is smoother by the chemical etching than by RIE. The roughness of the present wire surface is within 1 μm.

The vibrating wire was mounted in a superconducting magnet. A synthesizer oscillator applied a current into the vibrating wire and an induced voltage due to

[1] E-mail:hideo@sci.osaka-cu.ac.jp

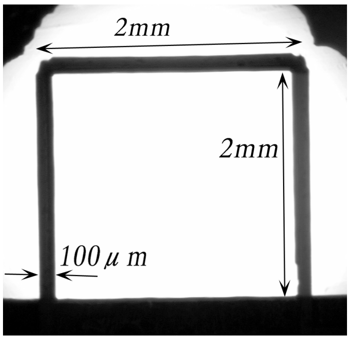

Fig. 1. Photograph of the silicon vibrating wire. The vibrating part is free in the open window of silicon wafer.

a motion by Lorentz force was detected with a Lock-in amplifier. The resistance of the vibrating wire is 4 Ω at 4.2 K. Because of the non-superconducting lead we estimated the induced voltage by subtracting a voltage due to the resistance.

3. Results and Discussion

We have investigated the characteristics of the vibrating wire in vacuum at 4.2K in a magnetic field of 50 mT. Driving the wire at a peak velocity of 7.6 mm/s we found a quality factor (Q) of 1.2×10^5 at a resonant frequency of 8.7 kHz. The obtained Q value is much higher than conventional Nb-Ti vibrating wires and four times higher than that of the previous silicon vibrating wire [7]. The higher Q is attributable to the quality of a silicon wafer. The resistivity of our silicon wafer is higher than 25 mΩ·cm of the wafer in the Grenoble study [7]. This indicates lower impurities in our wafer. Since impurities in a silicon oscillator cause an energy loss [5], the higher Q result is attributable to low impurities in the silicon wire.

We have also measured the Q value at various wire velocities as shown in Fig. 2. The Q value remains fairly constant at low velocities and decreases with increasing velocity above 2 mm/s. In the Lancaster studies [3,4] the quantized vortices and the quantum turbulences are created by a vibrating wire moving at maximum velocities around the Cooper pair breaking velocity of 9 mm/s. Since the silicon vibrating wire has still high Q up to 100 mm/s, it is expected that a vortex creation can be detected easily.

In the present wire we used evaporated gold as an electric lead. Because of non-superconducting lead a heat in the wire is generated by an applied current. At a wire velocity of 10 mm/s in vacuum an applied current is 7.6 μA_{p-p}, which causes a heat of 30 pW. Although the large Kapitza resistance prevents such a small heat leak into superfluid ^{3}He, the heat leak might

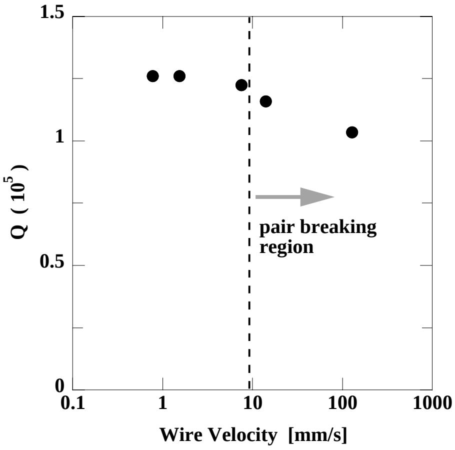

Fig. 2. Quality factor (Q) of the silicon vibrating wire as a function of maximum velocity for a wire moving.

cause a temperature gradient. In this case superconductor such as niobium is necessary for reducing heat leak. Disappearance of a voltage due to a superconducting lead also improves the signal to noise ratio of the silicon vibrating wire.

4. Conclusion

We have fabricated a vibrating wire from single crystal silicon. The obtained quality factor (Q) in vacuum at 4.2 K is much higher than the conventional Nb-Ti vibrating wire. The wire velocity dependence of Q implies that the silicon vibrating wire can detect a vortex creation in superfluid ^{3}He.

Acknowledgements

We are very grateful to Dr. T. Yotsuya for excellent advice about the micro-fabrication from a silicon wafer.

References

[1] M. Niemetz, H. Kerscher, W. Schoepe, J. Low Temp. Phys. **126** (2002) 287.

[2] S. I. Davis, P. C. Hendry, P. V. E. McClintock, Physica **280B** (2000) 43.

[3] D. I. Bradley, Phys. Rev. Lett. **84** (2000) 1252.

[4] S. N. Fisher, *et. al.*, Phys. Rev. Lett. **86** (2001) 244.

[5] R. E. Mihailovich, J. M. Parpia, Phys. Rev. Lett. **68** (1992) 3052.

[6] G. Stemme, J. Micromech. Microeng. **1** (1991) 113.

[7] S. Triqueneaux, *et. al.*, Physica **284-288B** (2000) 2141.