ELECTRIC FIELD STRUCTURE ON THE SURFACE OF SUPERCONDUCTING Pb-In SLAB IN LONGITUDINAL MAGNETIC FIELD

A. Shimogawa, N. Morita*, E. S. Otabe and T. Matsushita

Department of Computer Science and Electronics, Kyushu Institute of Technology, 680–4 Kawazu, Iizuka 820, Japan
*present address: Isahaya Electric Corporation, 1830–25, Kaizu-Cho, Isahaya 854, Japan

ABSTRACT

The structure of electric field on the surface of superconducting Pb-In slab samples was measured under the longitudinal magnetic field. A region with a negative electric field was observed as well as in a cylindrical sample. However, the obtained structure was different from the helical one observed by Ezaki and Irie for a cylindrical sample. The negative electric field originates from the term of $\boldsymbol{B} \times \boldsymbol{v}$ and appears at a position where the flux lines are pushed out of the sample, where $\boldsymbol{B}$ and $\boldsymbol{v}$ are the magnetic flux density and the velocity of flux lines, respectively. It was found that the averaged resistivity increased with increasing magnetic field. This result is similar to that in the transverse magnetic field and can be interpreted in terms of the Bardeen-Stephen model. As a result it is concluded that the energy dissipation in the longitudinal field is also caused by the motion of flux lines.

KEYWORDS: longitudinal magnetic field, negative electric field, Josephson equation, Bardeen-Stephen model, force-free moment

INTRODUCTION

When a magnetic field is applied parallel to a superconductor carrying a transport current, peculiar phenomena are observed. One of them is an appearance of a negative electric field in the resistive state and a deviation from the Josephson equation [1]. Since the Lorentz force does not work on flux lines under the longitudinal magnetic field, it may be believed that the energy dissipation is not caused by the motion of the flux lines under this field. However, it is expected that the moment proportional to the current density works on the flux lines which contain a torsional shear caused by the force-free current [2]. This moment is called the force-free moment. In the case of a cylindrical sample the energy dissipation was theoretically shown to be caused by the motion of the flux lines driven by it [3]. On the other hand, the mechanism of the energy dissipation in high T_c superconductors under the longitudinal field has not yet be clarified. However, these superconductors are usually of a slab geometry. As the first step for the purpose, the electric field structure on the surface was measured for superconducting Pb-In slab samples under the longitudinal magnetic field to investigate the mechanism of the energy dissipation in a slab geometry. The obtained results are discussed.

EXPERIMENTS

The samples measured in this study were Pb-60at%In alloy. These were rolled to a slab geometry and cut into a shape of bridge to reduce the effect of heat generated at contacts to current leads. The width, w, the thickness, t, and the length of the narrow region of bridge, l, of each sample are listed in Table 1.

Table 1. Size of samples.

Sample	w(mm)	t(mm)	l(mm)
1	1.70	0.18	20.00
2	1.86	0.23	10.00
3	2.42	0.22	13.19

Voltage terminals were attached to the sample by an electric discharge method. Figure 1 shows arrangements of voltage terminals. The spacing of voltage terminals was 1mm for samples 1 and 3 and 2mm for sample 2. The I-V characteristics of these samples were measured at 4.2K in liquid helium under a longitudinal field. For comparison the I-V characteristics were also measured under a transverse field, i.e., the field normal to the current but parallel to the wide surface of the sample.

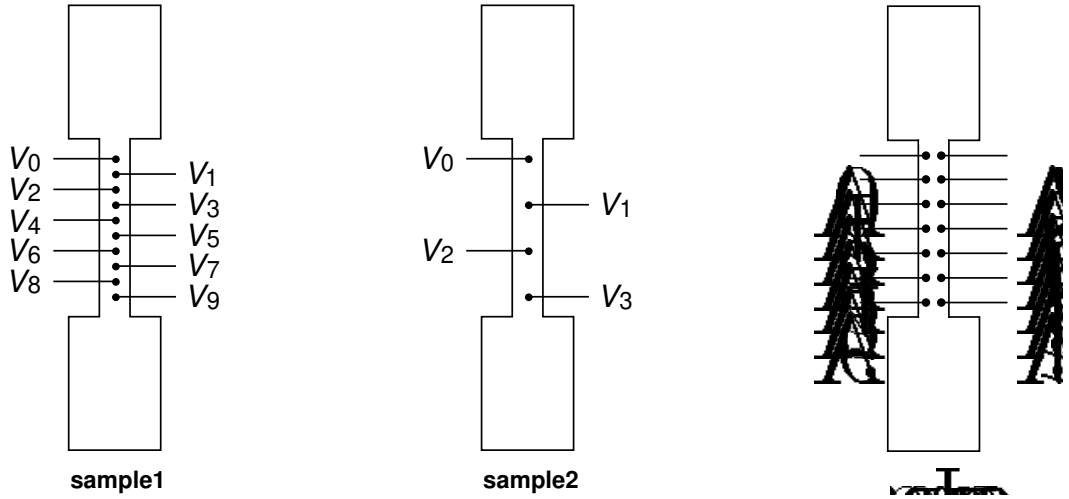

Fig. 1. Arrangements of voltage terminals.

RESULTS AND DISCUSSION

Figure 2 shows examples of the observed I-V characteristics at several positions of sample 1. As a result, a negative electric field was observed between the voltage terminals V_1 and V_2. This is similar to the case of cylindrical sample [1]. Figure 3 shows the spatial variation in the differential resistivity for sample 3. It is found that the resistivity varies depending on position and takes a negative value in V_7-V_6 and V_9-V_8 for the external field, B_e, higher than 50 mT. The self field of the current at the surface, B_I, amounts to about 12 mT at B_e=50 mT. Therefore, it is found that such an electric field structure appears when the external magnetic field becomes sufficiently larger than the self-field. Similar structure was observed also for samples 1 and 2. These structures were different from a beautiful helical structure observed in the cylindrical sample. For example,

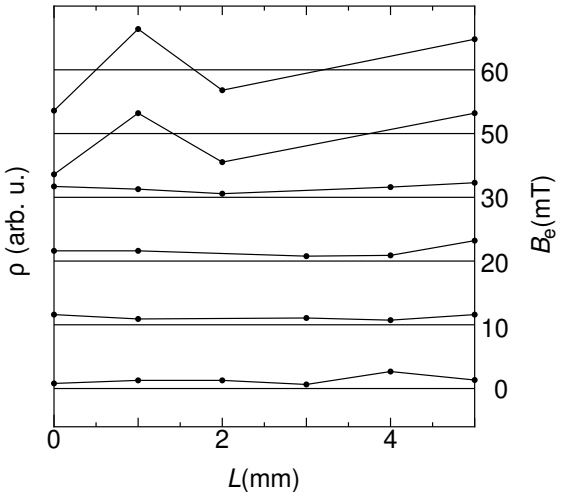

Fig. 2. I-V characteristics of sample 1 for each voltage terminal at $B_e = 0.10$ T.

Fig. 3. Spatial variation in resistivity.

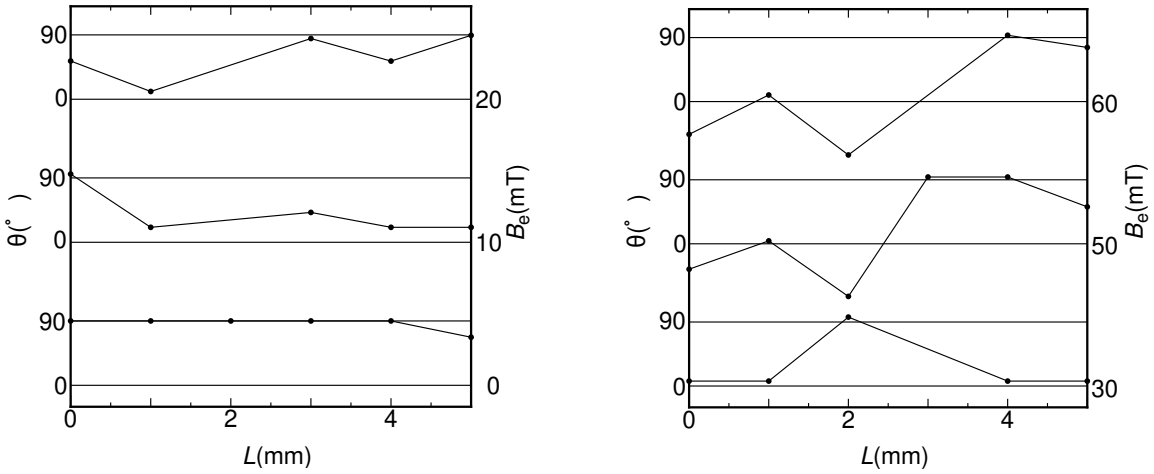

Fig. 4. Angle of E for B on the surface.

the helical pitch is estimated as 18.6 mm for the case of B_e=50 mT in Fig.3. Hence, the length of the sample is too short to see the complete structure. In addition, the flux lines partly go out of the sample and are not continuous from one end of the sample to the other. Thus, the present structure seems to be influenced by the slab geometry.

The direction of the electric field on the surface is determined for sample 3 by the potential differences in the longitudinal and the transverse directions, and the direction of the magnetic field is determined from the external and self fields. Figure 4 shows the spatial variation in the angle θ of $\boldsymbol{E}$ from $\boldsymbol{B}$. The angle θ is defined as show in Fig.5. It is found that the angle of the electric field varies from position to position. It is found that the angle of the electric field takes a negative value where the negative electric field is observed. In these regions the Poynting's vector is directed outward, and hence, the flux lines are expected to be pushed outward.

In general, the electric field under the longitudinal magnetic field deviates from the Josephson equation and is given by $\boldsymbol{E} = \boldsymbol{B} \times \boldsymbol{v} - \mathrm{grad}\Psi$, where $\boldsymbol{v}$ and Ψ are the velocity of flux lines and a scalar function, respectively. Therefore, the angle of the electric field from $\boldsymbol{B}$ varies from $\theta = \pm 90°$ due to the term of $-\mathrm{grad}\Psi$. Since the term of $\boldsymbol{B} \times \boldsymbol{v}$ gives rise to the negative electric field where flux lines come out of the superconductor, this supports the above speculation on the

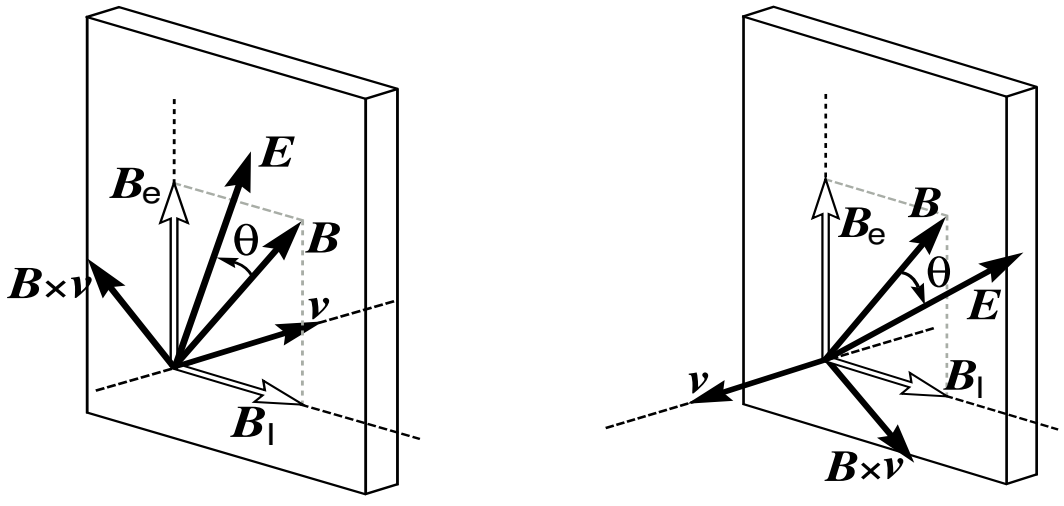

Fig. 5. Definition of angle θ. B_e and B_I are external magnetic field and self field of the current.

flux motion. That is, the negative electric field comes from $\boldsymbol{B} \times \boldsymbol{v}$ similarly to the case of the cylindrical sample.

The averaged differential resistivity was measured for sample 2 under the longitudinal and transverse magnetic fields. Figure 6 shows the magnetic field dependence of the averaged resistivity. It was found that the resistivity under the longitudinal field increased with increasing magnetic field similarly to that in the transverse field. This result agrees qualitatively with the interpretation of the Bardeen-Stephen model under the transverse magnetic field. That is, it is considered that the electric field originates from the motion of flux lines also in the superconductor of the slab geometry.

In a sufficiently long sample the term of $\boldsymbol{B} \times \boldsymbol{v}$ is reduced to 0 on an average due to the continuity of flux lines, and only the term of $-\mathrm{grad}\Psi$ remains. Therefore, it is considered that the Bardeen-Stephen model stands for only the term of $-\mathrm{grad}\Psi$.

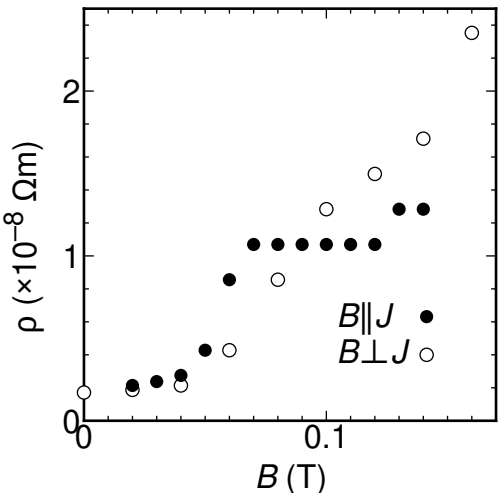

Fig. 6. Magnetic field dependence of averaged resistivity in longitudinal(•) and transverse(○) magnetic fields.

CONCLUSION

The structure of electric field was measured for three Pb-In slab samples under the longitudinal magnetic field and the following results were obtained:

1. The negative electric field was observed as well as in the cylindrical sample. However, the observed structure was different from that of the cylindrical sample. This seems to be attributed to the slab geometry of the sample.

2. The angle of the electric field from the magnetic field on the surface has a negative value at the position where the negative electric field appears. This suggests that the negative electric field is caused by the flux motion directed outwards the sample.

3. The averaged resistivity increases with increasing B and the result agrees with the interpretation of the Bardeen-Stephen model.

It is concluded from these results that the energy dissipation in the slab sample under the longitudinal field is also caused by the motion of flux lines.

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