Study of vortex configuration in the mixed state of a-W/Si multilayers

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Abstract

Configuration of vortices in highly tilted fields have been studied on amorphous W/Si multilayers with strong (3D) and weak (quasi-2D) layer coupling through the simultaneous measurements of electric fields in the film plane, E_x and E_y, as a function of current density J , where $x\|J$. We observe in the 3D sample the vortices move as the tilted lines around the glass transition and gradually change the configuration to the kinked lines with decreasing temperature. In the quasi-2D sample, only the dynamics of 2D pancake vortices has been observed at low J.

Key words: vortex line configuration; crossing lattice; W/Si multilayer; current-voltage characteristics

Recent studies on the mixed state of high T_c superconductors have made significant progress in understanding the novel vortex states. Especially, for the magnetic fields H inclined from the c axis, a variety of vortex configurations have been proposed, such as tilted line [1], kinked line [1,2], and crossing (combined) lattice [1,3]. Since the peculiar configurations originate from the layered crystal structure, it is possible to apply these concepts to the vortices in multilayer superconductors, which have an advantage of controlling the anisotropy.

In this work, we have studied the vortex motion and configuration in W/Si superconducting multilayers with strong (3D) and weak (qusi-2D) interlayer coupling by the measurements of electric field - current density (E-J) characteristics for two components under a special condition of inclined H as shown below [4]. The variation of the vortex configuration with degree of anisotropy is demonstrated.

Figure 1 shows the directions of J and H used in the measurements, where $\mathbf{J}$ is along the x axis and $\mathbf{H} = (H_0, H_0, \delta H_0)$ with $\delta \sim 0.15$. In this condition, Lorents
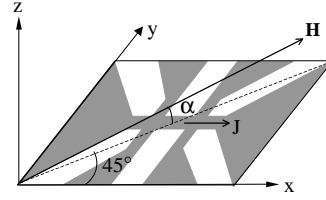
Fig. 1. A schematic drawing for the experimental condition, showing the sample and relationship between H and J. The tilted angle $\alpha \simeq 7°$.

force $\mathbf{F}_L = \mu_0(0, -\delta J H_0, J H_0)$ moves the vortices with a velocity $\mathbf{v} = (0, -v_y, v_z)$, which yield the electric field $\mathbf{E} = (E_x, E_y) = \mu_0(v_z H_0 + \delta v_y H_0, -v_z H_0)$. Here $v_y, v_z > 0$. When the vortices enter the sample as tilted lines along $\mathbf{H}$, they move along $\mathbf{F}_L$ and $E_x \simeq -E_y$ would be observed because v_z becomes the main part of the motion. On the other hand, when v_z is suppressed by the strong layer pinning (intrinsic pinning), $-E_y$ becomes smaller than E_x. In the 2D case, only the motion of pancake vortices would result in $E_y = 0$. Therefore, the simultaneous measurements of E_x and E_y give us a direct information about the motion of vortices, reflecting the vortex configuration.
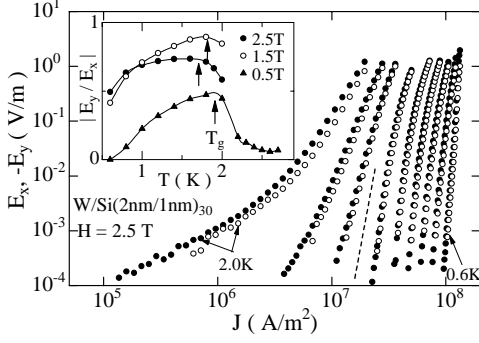
Fig. 2. E-J characteristics of WS21 for two electric fields, E_x (●) and $-E_y$ (○), in $H = 2.5$ T. Temperature range is from 2.0 K to 0.6 K in steps of 0.1K (2.0 K - 1.8 K) and 0.2K (1.8 K - 0.6 K). The inset shows the ratio $-E_y/E_x$ of the same sample at various H as a function of T.

Fig. 3. E-J characteristics of WS24 for two electric fields, E_x (●) and $-E_y$ (○), in $H = 0.5$ T. Temperature range is from 1.4 K to 0.6 K in steps of 0.2 K. The inset shows $E_y(J)$ of the same sample in a linear scale.

Amorphous W/Si multilayers were fabricated by an UHV evaporation method on oxidized Si(100) substrates [5]. Two kinds of samples, $[\text{W/Si}(2\text{nm}/1\text{nm})]_{\times 30}$ (WS21) and $[\text{W/Si}(2\text{nm}/4\text{nm})]_{\times 22}$ (WS24), were prepared. The interlayer coupling between the W layers is strong for WS21 (3D) and very weak for WS24 (qusi-2D) from our previous work [5]. The superconducting transition temperatures are 3.0 K and 2.0 K for WS21 and WS24, respectively. For the measurements of $E_x(J)$ and $E_y(J)$ characteristics, the samples were patterned into six-point configuration as shown in Fig. 1 with 700 μm in length and 200 μm in width.

Figure 2 shows two typical sets of $E(J)$ characteristics of WS21 for E_x and $-E_y$ in $H = 2.5$ T. Similar types of $E_{x,y}(J)$ curves are observed in all H studied. With decreasing T, the curvature of $E_x(J)$ on log-log plots changes from positive to negative one below T_g (dashed line in Fig. 2). This is the standard behavior regarded as the vortex glass transition [6,7]. It is noted that the trace of $-E_y(J)$ become close to that of $E_x(J)$ around T_g. This implies that the vortices move along $\mathbf{F}_L$ across the film plane. Thus, the vortices form correlated lines, which is tilted nearly along $\mathbf{H}$, around T_g in WS21. In the inset of Fig. 2, we plot the ratio of $-E_y/E_x$ at J with $E_x = 1 \times 10^{-1}$ V/m as a function of T. The ratio shows the peak at T_g and decreases with decreasing T. The peak corresponds to the development of tilted vortex line with diverging of correlation length $\xi_g \sim |T - T_g|^{-\nu}$ with ν the static exponent [6]. The reduction of the ratio can be explained by the effect of the intrinsic pinning that becomes remarkable at low T. The gradual change in the vortex configuration from the tilted line to the kinked one occurs.

In Fig. 3, $E_{x,y}(J)$ curves for WS24 in $H = 0.5$ T are shown. As well as the case of WS21, the curvature change in $E_x(J)$ in log-log scale is observed. However, the sign of correlated motion is not found in $E_y(J)$, which is very small and even has positive values at
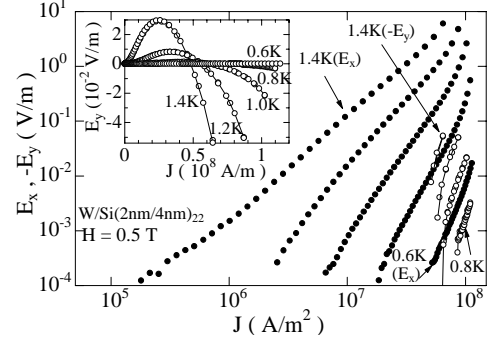
a low current region as shown in the inset of Fig. 3. The positive value cannot arise from the motion of in-plane vortex component, but be ascribed to the velocity drift of out-of-plane vortex component (pancake) due to the Magnus force. Thus, $E_x(J)$ and $E_y(J)$ at low J mainly result from the easy motion of pancake vortices. At high current region, the negative E_y emerges although the absolute value is still much smaller than E_x. This indicates the existence of the in-plane vortex component, which is hard to move along the z direction due to the layer structure. Considering these results, it may be natural that the vortex configuration in WS24 may consist of in-plane and out-of-plane vortices, which move separately as in crossing (combined) lattice state [1,3].

In conclusion, different kinds of vortex motions are observed in the W/Si multilayers with strong and weak interlayer coupling. These reflect the contrastive vortex configurations, the correlated line and the separation of in-plane and out-of-plane vortices.

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