Direct numerical confirmation of pinning-induced sign change in the superconducting Hall effect in type-II superconductors

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(Received 25 November 2009; revised manuscript received 3 December 2010; published 21 January 2011)

Using the time-dependent Ginzburg-Landau equation with the complex relaxation time and the Maxwell equation, we systematically examine transverse motion of vortex dynamics in the presence of pinning disorders. Consequently, in the plastic flow phase in which moving and pinned vortices coexist, we find that the Hall voltage can generally change its sign. The origin of the sign change is ascribed to the fact that moving vortices are caused to strongly drift by the circular current of pinned vortices and the enforced transverse moving direction becomes opposite to that of the transport current. This suggests that the Hall sign change is a behavior common in all disordered type-II superconductors. In this paper, we discuss conditions to observe such an intrinsic effect and explain experimental results reported in the literature on the basis of this effect.

DOI: 10.1103/PhysRevB.83.024507 PACS number(s): 74.25.Uv, 74.20.De, 74.25.F−

I. INTRODUCTION

Since the discovery of cuprate high-T_c superconductors, much attention has been devoted to vortex dynamics not only in superconductors but also in various superfluids from liquid helium to atomic gas. In particular, vortex pinning dynamics under disorders inevitable in superconducting materials is a central issue of vortex physics because of its deep relations to industrial applications. In this paper, we numerically examine vortex pinning dynamics and give an explanation for a controversial topic in vortex physics, i.e., sign change in the superconducting Hall effect (the Hall anomaly).[1–4]

The Hall anomaly is a long-standing unsolved problem. From the viewpoint of a single-vortex dynamics, the Hall effect is related to the nondissipative transverse force (or the vortex velocity part of the Magnus force) acting on a vortex.[5–10] The equation of motion for a single moving vortex has been intensively investigated;[11] nevertheless the Hall anomaly is still not fully understood. A controversial struggle is whether pinning (or disorder) can be an origin of the Hall anomaly,[12–18] where the system may not be described by a single-vortex dynamics, but by many vortices with different relative velocities due to vortex pinning.[10,14,15] If the Hall anomaly is caused by vortex pinning, it then indicates that the sign reversal is not limited in particular superconductors, but is universal for all type-II superconductors including disorders. We will prove that the idea is really true by numerically solving the time-dependent Ginzburg–Landau (TDGL) equation with complex relaxation time[19] and the Maxwell equation. This is a direct confirmation of the pinning-induced sign change without simplification and modeling.

The vortex dynamical phases under disorders are roughly classified into two types, i.e., plastic and collective flow phases.[20] The former phase appears in the vicinity of the critical current, and moving and pinned stationary vortices coexist. Then, the moving vortices may be locally drifted by the circular current of the pinned vortices. At a given instant the *local* current determines the *local* vortex motion. This local vortex motion produces the *local* electric field. The averaging of the local electric field over time and space provides the *average* voltage. This average voltage is what is observed experimentally. The Hall coefficient is determined by the average voltage and the average current (= the externally applied current).

In numerical simulations, we find that the average Hall voltage indeed exhibits the sign change under the existence of disorders. Here, our presupposition is only threefold: (i) The system contains randomly distributed point disorders as vortex pinning sites. (ii) The simulations are based on the TDGL equation with complex relaxation time.[19] (iii) The imaginary part of the relaxation time is set positive so as to produce a positive Hall voltage in a uniform system without disorders. One of the messages of this paper is that just three assumptions, (i)–(iii), lead to a negative Hall voltage; namely, just the existence of disorders leads to the Hall anomaly. We will show simulation results for the longitudinal and the Hall voltage and then propose a possible interpretation of the sign change in the Hall voltage.

Before going into the details of the simulations, we outline our interpretation of the sign change, which is inferred from simulation results. First, let us consider the dynamics of a single vortex near a pinned one. The directional reversal of a moving single vortex can occur as follows. For instance, when the transverse force intrinsically acts on the moving vortex in directions upstream and downstream of the local current, respectively, depending on the electronic structure,[2,21] the direction drifted by a pinned vortex is opposite, as shown schematically in Fig. 1(a). Thus, the directional reversal of the vortex velocity along the applied current occurs near a pinned vortex. It is found that a pinned vortex is not just a symmetric repulsive potential, but an asymmetric one for a moving vortex. However, it is still not clear whether such a mechanism really results in Hall sign change as a whole (i.e., on average). A whole system contains many moving vortices and pinned ones, which interact with each other. In the plastic flow phase, the distances and relative directions between vortices vary over time and space. Therefore, the velocity direction of each vortex behaves variously and the

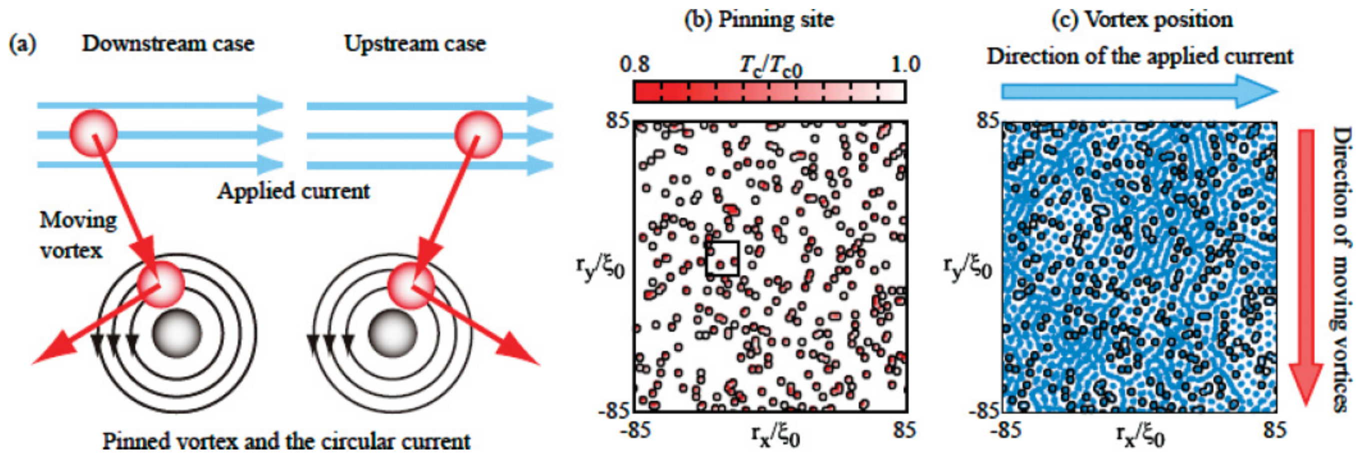

FIG. 1. (Color online) (a) A schematic figure of a moving single vortex driven by an applied current in the case of a complex TDGL relaxation rate in the presence of a pinned vortex. (b) The contour map of the local transition temperature $T_c(\boldsymbol{r})$. The closed curves (black) show the positions of pinning sites, and the shading color indicates the degree of the T_c suppression. (c) The superimposed snapshots of moving vortices in the time interval $4\times10^5 \leqslant t/t_0 \leqslant 6\times10^5$. The vortices are visualized at each instant by the contour plot (blue) of the order parameter at $\Delta/\Delta_0 = 0.2$. The positions of pinning sites are marked by black curves. $T/T_{c0} = 0.69$, $H_a/H_0 = 0.2$, and $j_x/j_0 = 5\times10^{-5}$.

above mechanism cannot act directly on an average vortex motion. Nevertheless, it is inferred from simulation results that near a pinning site the directional reversal of the vortex velocity indeed occurs locally at a given instant and the averaging over time and space results in a sign change in the average Hall voltage. That is, the mechanism acts on a local vortex motion and leads to a slight temptation of the velocity reversal statistically over many vortices.

II. MODELING AND TDGL SIMULATION

Let us present the system setup to confirm the pinning-induced sign change. We prepare a two-dimensional system in the xy plane. The external magnetic field H_a is applied perpendicular to the plane. To simulate vortex dynamics, we numerically solve the TDGL equation coupled with the Maxwell one written as[22–25]

$$\frac{\partial\Delta}{\partial t} = -\frac{c^2}{48\pi\kappa^2\xi_0^2\sigma\Gamma}\left[\left\{\left|\frac{\Delta}{\Delta_0}\right|^2 - \left(1-\frac{T}{T_c}\right)\right\}\Delta + \xi_0^2\left(\frac{\nabla}{i} - \frac{2e}{\hbar c}\boldsymbol{A}\right)^2\Delta\right], \qquad (1)$$

$$\frac{\sigma}{c}\frac{\partial\boldsymbol{A}}{\partial t} = \frac{\hbar c^2}{8\pi e\kappa^2\xi_0^2\Delta_0^2}\left[\Delta\left(-\frac{\nabla}{i} - \frac{2e}{\hbar c}\boldsymbol{A}\right)\Delta^* + \Delta^*\left(\frac{\nabla}{i} - \frac{2e}{\hbar c}\boldsymbol{A}\right)\Delta\right] - \frac{c}{4\pi}\mathrm{rot}\boldsymbol{H}. \qquad (2)$$

Here, we introduce local suppressions of the transition temperature $T_c(\boldsymbol{r})$, which act as vortex pinning sites. The order parameter Δ is normalized by its mean field value at the zero temperature without the magnetic field, Δ_0, and time t, vector potential $\boldsymbol{A}$, and magnetic field $\boldsymbol{H}$ are done by $t_0 = 4\pi\kappa^2\xi_0^2\sigma/c^2$, $A_0 = \phi_0/(2\pi\xi_0)$, and $H_0 = \phi_0/(2\pi\xi_0^2)$, respectively, where ξ_0, κ, σ, c, and $\phi_0[= 2\pi\hbar c/(2e)]$ are the zero-temperature coherence length, the Ginzburg–Landau parameter, the normal-state longitudinal conductance, the light velocity, and the flux quantum, respectively. To keep the gauge invariance of Eqs. (1) and (2) on numerical grids, we use the link variable $U_\mu^{ij} = \exp[-i\int_{r_i}^{r_j}(A_\mu/A_0)d\mu/\xi_0]$, where μ stands for x or y.[22–25] The magnetic field $\boldsymbol{H}$ is given by the Stokes' theorem $\int_S(\boldsymbol{H}/H_0)\cdot\boldsymbol{n}dS/\xi_0^2 = \int_c(\boldsymbol{A}/A_0)\cdot d\boldsymbol{l}/\xi_0$, and the electric field is calculated by $E_\mu = -(A_0/t_0)\int_{\bar{S}}\partial(A_\mu/A_0)/\partial(t/t_0)d^2r/\bar{S}$, where $\bar{S}$ is the unit plaquette surrounded by link variables. We evaluate the longitudinal and the Hall voltage from E_μ. In order to concentrate on the vortex contribution to the Hall voltage, we neglect the normal-state Hall conductivity in Eq. (2) for clarity. Instead, the dimensionless relaxation rate Γ in Eq. (1) is set to a complex number whose magnitude and ratio of the imaginary part depend on the electronic structure. According to Ref. 26, $1/\Gamma$ is related to the forces acting on each moving vortex. If we set $1/\Gamma$ pure real, the transverse force and the resulting Hall voltage are zero. On the other hand, a finite imaginary part of $1/\Gamma$ brings about a transverse force, and the sign of the imaginary part controls the sign of the Hall effect.[2,21,26–28] *We keep the imaginary part positive and never change its value throughout this study*; i.e., the transverse force is always positive and unchanged. The present condition corresponds to the case shown in the left panel of Fig. 1(a). Under the condition of the fixed complex relaxation rate, we find that the Hall voltage amplitude diminishes and a sign reversal occurs in the plastic flow regime owing to moving vortices affected by the circular current around pinned vortices.

In the present simulation, the system size is $200\xi_0 \times 200\xi_0$, which is discretized by the square grid whose unit dimension is $\xi_0 \times \xi_0$. The external current is applied along the x direction, and a periodic boundary condition is imposed in this direction to eliminate edge boundary effects on the vortex motion. The remaining boundary edge perpendicular to the y direction relevant to vortex entry and escape is modeled as an interface between a superconductor and a normal metal. Around this interface, $T_c(\boldsymbol{r})$ is set $T_c/T_{c0} = 0.1r/\xi_0(r < 10\xi_0)$, where r is the distance from the interface and T_{c0} is the bulk value of T_c. The number of vortex pinning centers is 500 inside the present system $200\xi_0 \times 200\xi_0$. The size of each pinning center is $2\xi_0 \times 2\xi_0$, inside of which $T_c(\boldsymbol{r})$ is randomly suppressed in the range $0.8 \leqslant T_c/T_{c0} \leqslant 1$. The locations of pinning centers are randomly distributed, e.g., as shown in Fig. 1(b).

In the TDGL dynamical simulation, we prepare an initial state in the absence of both the applied current and the external field and then start to apply a current j_x and a target external field H_a at $t = 0$. The applied current density is always set as $j_x/j_0 = 5 \times 10^{-5}$, where $j_0[= \phi_0/(2\pi\xi_0^3)]$ is the depairing current. The GL parameter is $\kappa = 2.83$, and the minimal time step is $3 \times 10^{-3} t_0$. We fix $1/\Gamma = 1 + 0.3i$, which leads to a substantial ratio of the Hall voltage V_y to the longitudinal one V_x, i.e., $V_y/V_x \sim 0.2$, in the uniform current under no pinnings. Such a large imaginary value can give a striking contrast in the sign change of the Hall voltage. To avoid counting an interface influence on the voltage, e.g., an effect of the diamagnetic current, we take an average of the electric field within the region $-85 \leqslant r_{x(y)}/\xi_0 \leqslant 85$. The time average of the Hall voltage is taken over the time interval $4 \times 10^5 \leqslant t/t_0 \leqslant 6 \times 10^5$, during which vortex motions are fully steady.

III. SIMULATION RESULTS

Let us present simulation results. First, the temperature (T) dependencies of the longitudinal and Hall voltages under the applied fields $H_a/H_0 = 0.15$ and 0.2 are displayed in Figs. 2(a) and 2(b), respectively. The longitudinal voltage V_x monotonically decreases with decreasing T in both cases. Although the Hall voltage V_y exhibits nonmonotonic behavior, both the signs become negative in the region of the small longitudinal voltage V_x. Here, one might imagine that this negative transverse voltage occurs because of guided vortex flow lines[16] formed accidentally by clustering of pinned sites. However, it is not always the case, although such a happening actually occurs. In order to confirm it, we just reverse the magnetic field direction only and repeat the same simulation. Then, since the pinning-site distribution is the same as in the previous simulation, the same guiding line principally develops even on the field reversal. This is the case in disorders composed of rather strong pinning sites as in the present simulation. Thus, we can never expect the sign reversal on the field reversal if the guiding is only an origin of the sign reversal. While the sign reversal actually disappears for the field $H_a/H_0 = 0.15$ [Fig. 2(c)], it is surprisingly kept on for another field $H_a/H_0 = 0.2$ [Fig. 2(d)]. This suggests that there is an intrinsic origin of the sign reversal beyond the guiding effects. We further perform simulations (not shown) under other random vortex-pinning distributions, (II)–(IV), and repeat the same simulations with the field direction reversal, ($\overline{\mathrm{II}}$)–($\overline{\mathrm{IV}}$). These results are summarized in Table I. In the results, we notice that there are some cases where the vortex guiding seems to mainly cause the sign change as the distributions II and III, in which the Hall sign differs on the field inversion. However, the sign reversal is preserved on the field direction reversal for the other distributions I and IV. Thus, we can draw a conclusion that the sign reversal occurs as an intrinsic effect although the guiding effect is also non-negligible in plastic flow phases. In particular, we point out that the guiding effect is never non-negligible in small-sample-size simulations. Indeed, in smaller scale simulations, we frequently confirm such cases; i.e., strong guiding masks the intrinsic effect. Therefore, one naturally expects that the intrinsic mechanism fully dominates in sufficiently large samples as experiments. But, such conclusive confirmation is a future task for a present heavy simulation such as the TDGL equation, since the plastic flow simulation basically requires a very long time calculation and the disorder averaging also demands much more CPU time.

TABLE I. Yes/no table in terms of the sign reversal of the Hall voltage for different random pinning distributions (I)–(IV) and their field inversion cases ($\bar{\mathrm{I}}$)–($\overline{\mathrm{IV}}$). "Y(N)" means that the sign reversal is observable (or not).

	I	$\bar{\mathrm{I}}$	II	$\overline{\mathrm{II}}$	III	$\overline{\mathrm{III}}$	IV	$\overline{\mathrm{IV}}$
$H_a/H_0 = 0.15$	Y	N	Y	N	N	Y	Y	Y
$H_a/H_0 = 0.2$	Y	Y	Y	N	N	Y	Y	Y

We have shown so far that the Hall voltage as a whole, i.e., the averaged transverse motion of vortices, can indeed exhibit the sign change under the influence of random pinning distributions. Here, we pay attention to its origin again. To elucidate it, let us focus on detailed vortex dynamics around

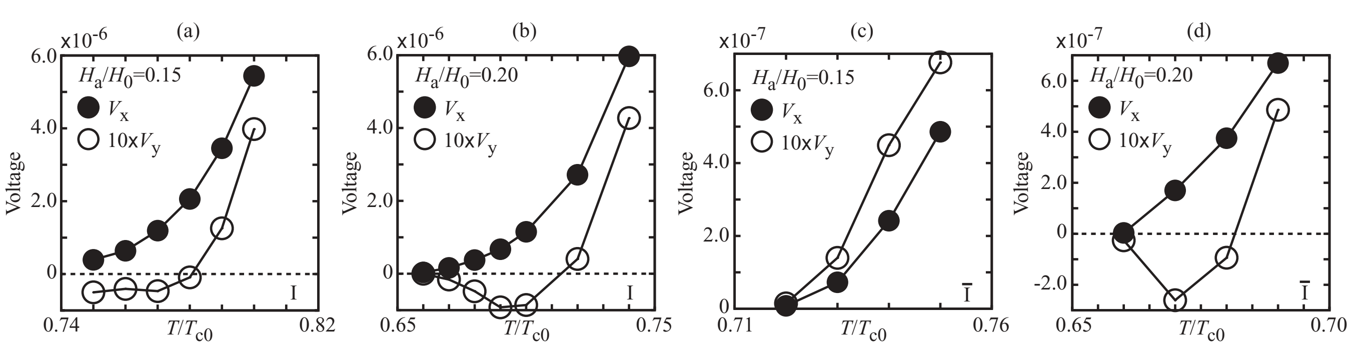

FIG. 2. Temperature dependencies of the longitudinal (V_x) and Hall (V_y) voltages in units of $A_0\xi_0/t_0$. The solid (open) circles indicate the longitudinal (Hall) voltage. Note that the Hall voltage is plotted in the ten times larger scale. The voltages are calculated from the electric field averaged over $-85 \leqslant r_{x(y)}/\xi_0 \leqslant 85$ and $4 \times 10^5 \leqslant t/t_0 \leqslant 6 \times 10^5$. The applied current is $j_x/j_0 = 5 \times 10^{-5}$. The applied field is $H_a/H_0 = 0.15$ for panels (a) and (c) and $H_a/H_0 = 0.2$ for panels (b) and (d). The results in panels (a) and (b) are obtained for the distribution of pinning sites shown in Fig. 1(b), while the same distribution is used but the bottom is inverted into the top for moving vortices to obtain the results in panels (c) and (d) (see text).

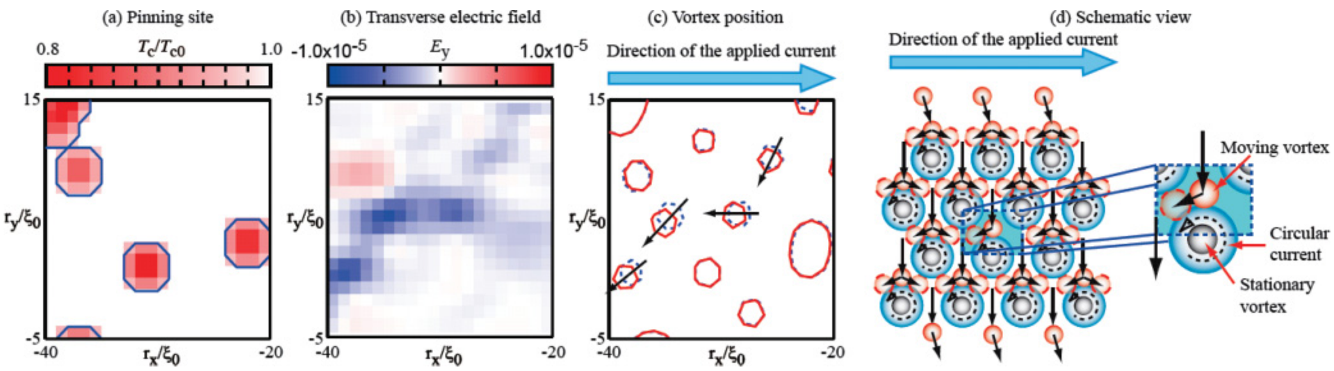

FIG. 3. (Color online) (a) The distribution of pinning sites in the focused area, whose location is marked by the small box in Fig. 1(b). (b) The transverse electric field in the area for $T/T_c = 0.69$, $H_a/H_0 = 0.2$, and $j_x/j_0 = 5 \times 10^{-5}$. The data are averaged over $5.8 \times 10^5 \leqslant t/t_0 \leqslant 5.84 \times 10^5$. (c)The vortex positions at $t/t_0 = 5.8 \times 10^5$ and 5.84×10^5 through the contour plot of the order parameter amplitude. The arrows indicate the moving directions. (d) The schematic representation of moving vortices around stationary vortices.

vortex-pinning sites. Figure 3(a) is an enlarged figure of a small area whose location is marked in Fig. 1(b). The distribution of the transverse electric field averaged over $5.8 \times 10^5 \leqslant t/t_0 \leqslant 5.84 \times 10^5$ is shown in Fig. 3(b), where the sign of the transverse field is always negative near the vortex-pinning sites. In addition, by monitoring the vortex position at 5.8×10^5 t_0 and 5.84×10^5 t_0 in the displayed area, the focused vortices approaching the pinned ones are found to flow against the applied transport current [Fig. 3(c)]. These observed results support our scenario. The pinned vortex has a circular current flow around its core. The flow direction is opposite to that of the applied current in its top half as schematically shown in Fig. 3(d), where the transverse force direction of the moving vortex is opposite to that of the free flow case. That is, the moving vortex penetrating into the circular-current flow range is drifted into the opposite direction to the applied current. This is because the positive imaginary part of Γ fixed in this paper always drives the moving vortex into the downstream side of the local current flow. In addition, we notice that the mechanism demands the presence of sufficiently dense pinned vortices. In other words, moving vortices should be scattered at sufficiently frequent intervals by pinned vortices from an entry at sample edge to an exit. The repeatedly scattered vortices show opposite-direction motion, which occurs at many locations in Fig. 1(c). Of course, depending on the instantaneous position and velocity of each vortex relative to pinned vortices, one part of vortices move in the downstream direction of the applied current flow and the other part move in the upstream direction at each instant. It appears that a slight temptation of the upstream-direction motion occurs statistically over many vortices because each pinned vortex is not just a symmetric repulsive potential, but an asymmetric one with the circular current around it. This is the mechanism of the Hall sign change observed from the numerical simulations, which we outline schematically in Figs. 1(a) (left panel) and 3(d).

IV. DISCUSSION AND CONCLUSION

Finally, let us discuss the present results through a comparison with experiments. The present calculations have revealed that, when the vortex dynamics change from the collective flow to the plastic flow phase, the moving vortex frequently reverses its transverse moving direction. This directional reversal principally requires the plastic flow phase as a vortex dynamical phase. In other words, this effect is universal for all type-II superconductors as long as disorders or pinning sites sufficient to keep the plastic flow phase are introduced inside the sample. In high-T_c cuprate superconductors, double sign changes in addition to single ones have been frequently observed depending on the sample.[29] These experimental results can be explained on the basis of the present result as follows. When the current carrying phase changes from the normal to the flux flow phase, the first sign change occurs. This can be interpreted by the idea that there is a difference between the Hall effect in the normal phase and the fluctuation Hall effect near the superconducting transition via the relaxation of the order parameter.[2,21,26–28] This is a microscopic sign change mechanism depending on the electronic structure. On the other hand, it has been observed that the final reversals strongly depend on the sample quality or the rate of artificial damage to enrich pinning centers.[30] Thus, the final sign change is attributed to the pinning-induced one as confirmed by the present simulation. Moreover, such a sign change is also well known to be sensitively dependent on the sample quality in conventional type-II superconductors.

In conclusion, we performed TDGL simulations with the complex relaxation time to confirm the pinning induced sign reversal of the superconducting Hall effect. Consequently, the simulation revealed that the sign change can occur when the current carrying state enters the plastic flow phase from the collective flux flow one. Moreover, the detailed analysis on the vortex motions successfully explained that, when the circular current of the pinned vortex strongly drifts the moving vortex in the plastic flow phase, the moving vortex feels the transverse force causing the Hall sign change. Our numerical simulations elucidate that the averaged vortex motion as a whole indeed leads to the Hall sign change under the influence of such circular currents around randomly distributed vortex pinnings. These results suggest that the Hall sign change is an indicator of vortex dynamical phases in disordered type-II superconductors.

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