Negative resistance in I-V characteristics and 2D vortex dynamics in a-W/Si multilayer superconductors with periodic antidot arrays

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Abstract

We have examined the vortex dynamics in W/Si multilayers with the arrays of antidots in the form of square and triangular lattices. In the measurements of I-V characteristics as a function of temperature T and magnetic field H, we find a specific a feature that the $V(I)$ curves coincide irrespective of T. Especially the $V(I)$ curves with a negative slope are observed in the multilayer with triangular arrays.

Key words: vortex dynamics; antidot arrays; W/Si multilayer; current-voltage characteristic

Superconductors with regular pinning arrays show the attractive features originating from the periodicity of both pinning site and vortex lattice. Recently, the commensurability effect and the novel dynamical flow phases have been reported in various experiments on superconductor films with periodic micro holes and magnetic dots [1–4] and the simulations [5]. While the most works are conducted in the conditions that one vortex is trapped at a single pinning site, Bezryadin *et al.* [6] have experimentally shown the multiple vortices trapped at individual pinning sites with large size. The similar results have been demonstrated through numerical simulations [7]. It is now important to clarify the dynamics of the multivortex state. In this work, we have examined current-voltage (I-V) characteristics on the superconducting W/Si multilayers with periodic antidot arrays in the form of square and triangular lattices in the multivortex state.

The samples in this work, $[\mathrm{W/Si(3nm/1nm)}]_{\times 10}$ (WS4) and $[\mathrm{W/Si(2nm/1nm)}]_{\times 10}$ (WS3) multilayers with square and triangle antidot array, respectively, were fabricated on oxidized Si(100) substrates using a high vacuum evaporation method [8]. To introduce

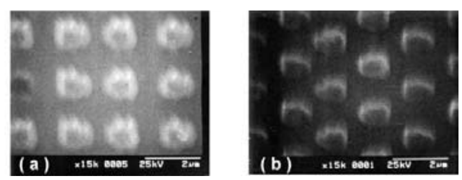

Fig. 1. SEM images of antidot arrays for (a) WS4 (square lattice) and (b) WS3 (trianglar lattice). For both samples the lattice constant is $d \simeq 2$ μm and the antidots have a diameter $\simeq 1$ μm.

the antidots, the array of the photoresist pillars with diameter of $\simeq 1$ μm and lattice spacing of $d \simeq 2$ μm were patterned on the substrates by electron beam lithography before the deposition. After the deposition followed by lift-off, we obtained the samples containing antidot arrays (80 μm x 40 μm) as shown in Fig. 1. The superconducting transition temperatures are 3.39 K and 2.82 K for WS4 and WS3, respectively. To investigate the dynamics of the multivortex state, the measurements are performed in magnetic fields $H \gg$ the matching field $B_\phi = \phi_0/d^2$ or $1.15\phi_0/d^2$ with ϕ_0 the flux quantum.

Figure 2 shows the typical sets of $V(I)$ curves for WS4 (square array) in $H = 0.2$ T. The remarkable fea-

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linear in the whole current range measured below T_a, indicative of the vortex solid phase, the drastic behavior shown in Figs. 2 and 3 comes from the dynamics of vortex lattice. In our measurement, the driving force works on the vortices in vertical direction of Fig. 1 with the applied current parallel to the horizontal direction. The vortex lattice in the narrow channels between the rows of antidots can flow almost freely as the vortex lattice correlation is weakened around the antidotes due to the positional disorder. This confined flow may lead to the T-independent linear $V(I)$ curves.

The decrease of the slope in $\log V$-$\log I$ curve from unity above I_{c1}, as well as the negative slope above I_{c2} for WS3, means that the number of vortices moving in the channel decreases with increasing current. Through the simulation of driven vortex lattice in periodic pinning arrays, Reichhardt *et al.* [5] demonstrate that when the driving force is strong enough in the field a little larger than B_ϕ, there appears a new 1D flow phase, where the vortices in the flow channels *between* the rows of pining site at low I are taken in the intermittent vortex motion *along* the rows at high I and then a drop in V occurs. In our case ($H \gg B_\phi$), part of the vortices in the channels might participate in such slow 1D motion, leading to the slope change in $\log V$-$\log I$. According to this idea, the negative slope for WS3 implies that the remarkable number of vortices change their paths into the motion along the rows of antidots.

In conclusion, the anomalous T independence and the slope change in the I-V characteristics are found in W/Si multilayer with periodic antidot arrays. These suggest that in the multivortex state there exist a variety of dynamic phases as a function of driving force.

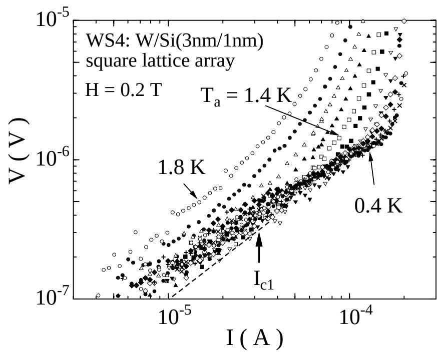

Fig. 2. I-V characteristics for the WS4 (square lattice arrays) in $H = 0.2$ T. Temperature range is from 1.8 K to 0.4 K in steps of 0.1 K. The broken line indecates a slope = 1.

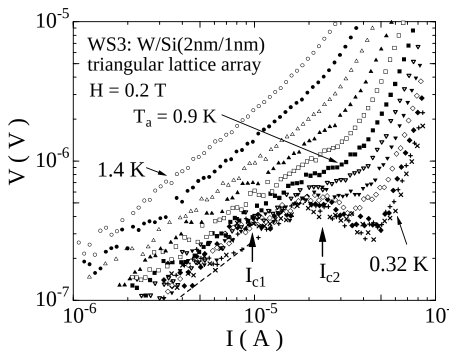

Fig. 3. I-V characteristics for the WS3 (triangular lattice arrays) in $H = 0.2$ T. Temperature range is from 1.4 K to 0.32 K in steps of 0.1 K (between 1.4 K and 0.4K). The broken line indecates a slope = 1.

ture is that with decreasing T, the $V(I)$ curves suddenly start to coincide below a characteristic temperature T_a with a linear slope in the low current region. Moreover, the slope of the collapsed curves in log-log scale changes to a lower value above the certain current $I_{c1} \sim 3 \times 10^{-5}$ A. The same type of behavior is observed in $H \geq 0.15$ T.

In Fig. 3, the sets of $V(I)$ curves for WS3 (triangular array) in $H = 0.2$ T are shown. As well as WS4, the traces of $V(I)$ curves becomes almost independent of T with a linear slope in a low current region below T_a and a small slope change also occurs at $I_{c1} \sim 1 \times 10^{-5}$ A. With increasing current further, however, the $V(I)$ exhibits the negative slope above another characteristic current I_{c2}. While the coincidence of the $V(I)$ curves is observed in a wide range of $H > 0.05$ T, the negative slope region shifts to higher current side with increasing H and disappears around $H = 0.3$ T.

The anomalies in the $V(I)$ curves are never observed in the regions of the same samples without antidots. Since the $V(I)$ curves in these regions become non-

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