An Alternative Interpretation of Multiple Josephson-vortex-Flow Branches in Intrinsic Josephson Junctions

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Josephson vortices in a static state introduced in stacked intrinsic Josephson junctions such as $Bi_2Sr_2CaCuO_{8+\delta}$ (Bi2212) are believed to form a regular triangular lattice in high-enough magnetic field in which Josephson vortices overwrap. The collectively moving Josephson vortex lattice is suggested as odds-on coherent terahertz microwave source and extensive studies to realize the THz microwave source by exploiting the Josephson vortex lattice has been performed. To idealize the THz wave emission from the moving Josephson vortex lattice, the possible way to manipulate the Josephson vortex lattice structure, especially to establish a rectangular lattice, has been studied. Recently, Dr. Bae has reported the observation of multiple branch structure so-called Josephson vortex flow branches (JVFBs) in the flux flow regime and explained it in terms of the resonance with discrete Josephson plasma modes so-called Kleiner modes and claimed the rectangular Josephson vortex lattice establishment. We, however, re-investigated the origin of the JVFBs by examining the evolving process in a relatively low field $H < 2$ T and concluded that the JVFBs come from the pinning and depinning of Josephson vortices in different layers rather than the resonance with Josephson plasma modes and lattice structure transformation. We fabricated Bi2212 single crystal into a stack sandwiched between two gold layers without a basal part by using the double-side cleaving technique and obtained current-voltage characteristics in the c-axis tunneling measurement in various external magnetic fields and temperatures. The total number of junctions N is determined to be 23 from the number of the zero field quasiparticle branches. As increasing in-plane magnetic field up to 2 T, we observed the usual Josephson vortex flow branches with the number 21 similar with the total number of junctions N along with the remnant quasiparticle branches and it suppresses as increasing field. The JVFBs is separated with the quasiparticle branches in a magnetic field higher than 2 T, however the multiple branch structure starts to appear around 1 T and it develops into the usual shape as increasing field strength. The current-voltage characteristics obtained in 1 T consists of 2 parts; a low-bias-current part in which the Josephson vortices are in static state, that is the voltage difference V_{diff} with the zero field QBs for the vortex motion is 0, and a high-bias-current part in which the Josephson vortices are in dynamic state, that is V_{diff} is nonzero. On the boundary of the two parts, the multiple branch structure JVFBs emerges, which means the JVFBs appear while the static Josephson vortices start to move layer by layer and the JVFBs represent pinning and depinning of Josephson vortices rather than collective motion in entire junctions. We believe that the moving Josephson vortex forms a triangular lattice in accordance with the consensus that oblique Josephson vortex lattice is unstable and a general way to establish an oblique or rectangular lattice does not exist. The transition from a static state to a dynamic state is observed in lower field $H < 0.5$ T in which Josephson vortex lattice formation is not expected and it agrees with our conclusion that the JVFBs arises from the depinning precess of Josephson vortices. We, also, investigated the JVFBs's dependence on the out of plane field strength and temperature and found that all the results are in agreement with the pinning-depinning model.