Digest of Tech. Papers The 8th Conf. (1976 International) on Solid State Devices, Tokyo

B-2-2

Dynamic behavior of long Josephson junctions

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For the purpose of utilizing Josephson tunnel junctions as switching devices, it is neccessary to study their dynamic behaviors. So far, reported analyses have been based on the lumped circuit model. With this model, however, it is not adequate to discuss the switching behavior of long ($L>\lambda_J$) or high current density junctions, because in such cases the Meissner effect in the junction is not negligible. Here L is the junction length and λ_J is the Josephson penetration depth. We have investigated the dynamic behavior of long Josephson junctions with the distributed circuit model by means of a computer simulation, and in this paper two types of the switching behavior are reported.

The sine-Gordon equation with a kinetic loss term added was numerically solved with a boundary condition which takes account of the effect of the external and self-induced magnetic field at the edges of the junction. Phase difference ϕ between two superconductors, magnetic field H and current density j in the junction were obtained as a function of space and time variables for the given external field H_e and junction total current I. The static solution, which was obtained with the same method as shown by Basavaiah and Broom,[1] was used as an initial condition for the dynamics. A typical example of the static distributions of H and j is shown in Fig. 1, where Φ is the total magnetic flux within the junction.

It is well known that a Josephson junction transfers to the voltage state when the junction current I exceeds the critical current I_c, and that the junction voltage V oscillates due to the AC Josephson effect. Figure 2 shows the time variation of Φ and $\bar{V}$ in case of $L=5\lambda_J$ and the normalized loss parameter $\Gamma=0.6$. Here $\bar{V}$ is the spatially averaged junction voltage in case of $\lambda_J=10\ \mu m$, $j_J=3.2\times10^7\ A/m^2$ and $t_J=0.35$ p sec. I and H_e are varied as shown in the I_c-H_e chart in Fig. 2. The junction, initially settled at the zero-voltage state with zero external field, transfers

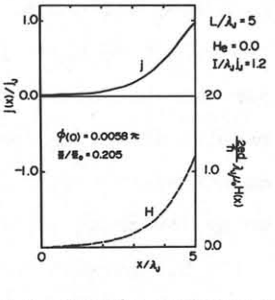


Fig.1 Static current and magnetic field distributions in the junction

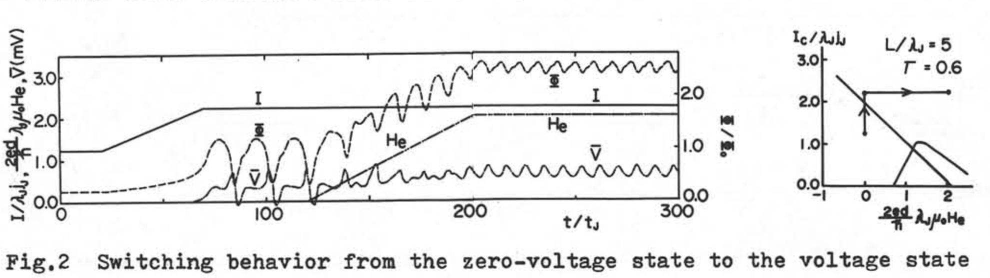


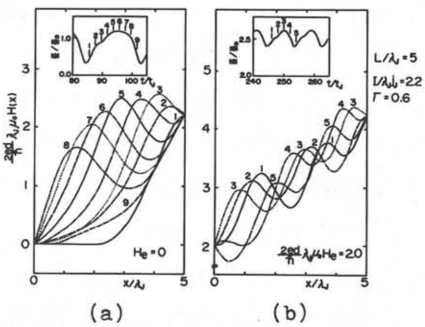
Fig.2 Switching behavior from the zero-voltage state to the voltage state

to the voltage state when I is increased above I_c. It must be noted that $\bar{\Phi}$ and $\bar{V}$ oscillates with the same period. Time variation of the magnetic field distribution in the junction is shown in Fig. 3(a), which indicates that the magnetic flux equivalent to the flux quantum is dragged into the junction from the right edge and travels toward left until it is driven out from the left edge. When H_e is increased, $\bar{\Phi}$ also increases as shown in Fig. 2. In this situation, the flux in the junction shows the multi-vortex state as indicated in Fig. 3(b), and the period of the oscillation is equal to the time for one vortex shift. It must be noted that the AC Josephson oscillation is originated from the flux flow in the junction.

Small Josephson junctions ($L \lesssim \lambda_J$) show Fraunhofer-like patterns in their I_c-H_e characteristics, but for long junctions ($L > \lambda_J$), the patterns deviate from them and overlap in the trailing edges of two neighboring vortex modes. Therfore it is possible to exhibit two different zero-voltage states for the given I and H_e. Figure 4 shows a switching behavior between the 0~1 vortex mode and the 1~2 vortex mode. The junction is set initially in the 0~1 mode, and then H_e is increased to exceed the threshold line from the 0~1 mode to the 1~2 mode under the condition that I is kept constant. When H_e intersects the threshold line, a transient voltage appears across the junction as shown in Fig. 4, but the junction settles to the zero-voltage state in the 1~2 mode after the inter-mode-switching is achieved. Similarly, it is possible to switch from the 1~2 mode to the 0~1 mode with decreasing H_e. It must be emphasized that the overlaped region of two neighboring vortex modes in the I_c-H_e characteristics can exhibit two stable zero-voltage states and the switching between them is also possible.

Dynamic behaviors of long Josephson junctions have been discussed concentrating on two types of the switching characteristics. Results presented here are useful for the understanding of pysical meaning of the AC Josephson effect as well as the quantitative design of the switching circuits using Josephson junctions.

(1) S.Basavaiah and R.F.Broom: IEEE Trans. Mag., MAG-11, 759, (1975)



(a) (b)

Fig.3 Time variation of the magnetic field distributions in two different voltage states shown in Fig.2

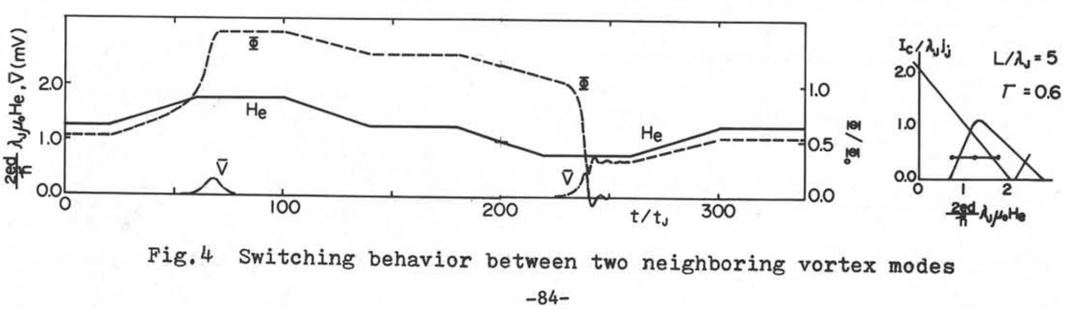


Fig.4 Switching behavior between two neighboring vortex modes