Abstract

We review our results on the investigation of the breakpoint phenomena in the stacks with finite number of intrinsic Josephson junctions in high temperature superconductors. New ideas concerning the breakpoint region structure are discussed as well.

Introduction

The current-voltage characteristic (IVC) of intrinsic Josephson junctions (IJJ) is characterized by a multiple branch structure [1-4] and the branches have a breakpoint region with its breakpoint current (BPC) and transition current to the another branch [5, 6]. The BPC is determined by the creation of the longitudinal plasma waves (LPW) with a definite wave number $k$, which depends on the coupling $\alpha$ and dissipation $\beta$ parameters, number of junctions in the stack $N$ and boundary conditions. In the framework of the CCJJ+DC model [7, 8] we generalize the McCumber-Steward dependence of the return current [9] for the case of IJJ in the HTSC and investigate the BPC on the outermost branch as a function of the coupling $\alpha$ and dissipation $\beta$ parameters for the stacks with different number of IJJ. It is shown that the $\alpha\beta$-dependence of the BPC is an instrument to determine the mode of LPW created at the breakpoint in the stacks with different number of junctions [10].

Breakpoint in the IV-characteristics

Fig. 1 shows the IVC of a stack of 10 IJJ at $\alpha = 1$, $\beta = 0.2$ and $\gamma = 0$. The dashed line corresponds to the result of calculations without noise (round of error less than $10^{-15}$, while the solid lines correspond to the result of calculations with a small noise in the current with it maximum in the interval $(-10^{-8}, +10^{-8})$. As we can see, there is a breakpoint region (BPR) on the outermost branch. Solving the equation for difference of phase differences for stack of $N$ junctions [5], we find the resonance region for the resonance between Josephson and plasma oscillations, which is shown in Fig.1(right).

Here $\beta(k) = \beta C$, $\Omega(k) = \Omega C$, $C = \sqrt{1 + 2\alpha(1 - \alpha \sin k)}$, where $\Omega$ the Josephson frequency, $k$ is wave vector of LPW. From the results of simulation
we find that the positions of the breakpoints coincide with the border of the resonance region. In this figure black dots (stripe) correspond to the breakpoint current $I_{BP}$ in the IVC for $k = \pi$ at different values of parameters $\alpha$ and $\beta$ [6].

### N-dependence

The IVC at periodic boundary condition (Fig.2, left) show the same behavior of the $I_{BP}$ and BPR width $w_{BP}$ for the stacks with odd $N$ as in the nonperiodic case, but for the stacks with even $N$ the value of the $I_{BP}$ does not depend on the $N$ and the BPR for these stacks is absent. The N-dependence of the BPR width $w_{BP}$ for stacks with even and odd number of junctions at $\gamma = 0$ (curves $1_{\text{even}}$ and $1_{\text{odd}}$) and periodic (curve $2_{\text{odd}}$) boundary conditions is shown in Fig.2 (right). The main feature here is a decrease of the BPR width with $N$ at large $N$. At small $N$ in the interval (3, 6) we observe the increase of the $w_{BP}$ with $N$.

### Influence of the coupling between junctions

At $\alpha = 0$ the IVC does not manifest the multibranch structure and the breakpoint coincides with the return current. The curves at $\alpha \neq 0$ have new features in comparison with the case without coupling. Particularly, they show a stronger increase of the $I_{BP}$ at small $\beta$, a plateau at $I_{BP} \approx 0.83$ and the small oscillation of the $I_{BP}$ on this plateau, and a transition to the non-hysteretic regime (second plateau) at smaller $\beta$ in compare with a case $\alpha = 0$. We change the coupling parameter $\alpha$ in the interval (0,8) by the step 0.1 and repeat the calculations of the $\beta$ - dependence of $I_{BP}$. By this method we build the 3-dimensional picture of the $\alpha \beta$-dependence of the $I_{BP}$ for stack with 10 IJJ, which is shown in Fig.3 (left).

Fig. 2: (Left) - IVC of the outermost branch for the stacks with different number of junctions at periodic BC; (Right) - the N-dependence of the BPR width $w_{BP}$ for stacks with even and odd number of junctions at $\gamma = 0$ (1) and periodic (2) boundary conditions (From Ref.[6]).

Fig. 3: (Left) - The $\alpha \beta$ - dependence of the $I_{BP}$ for stack of 10 IJJ (From Ref.[10]) ; (Right) – The simulated $\alpha$-dependence of the $I_{BP}$ for the stacks with 3, 6, 9 and 12 IJJ (a); 4, 8, 12 and 16 IJJ (b); 5, 10 and 15 IJJ (c) at $\beta = 0.3$. 

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Based on the idea of the parametric resonance in the stack of IJJ, a modeling of the $\alpha \beta$-dependence of the BPC have been done and a good qualitative agreement with the results of simulation have been obtained [10]. Comparison of the $\alpha$ - or $\beta$ -dependence of the $I_{BP}$ for stacks with different number of IJJ gives us a simple method (we call it as $k\alpha \beta$-method) to determine the wave numbers k of the LPW. Fig.3(right) shows the $\alpha$ - dependence of the $I_{BP}$ for the stacks with 3, 6, 9 and 12 IJJ (a); 4, 8, 12 and 16 IJJ (b); 5, 10 and 15 IJJ at $\beta$ = 0.3. It demonstrates that in some intervals of $\beta$ the stacks with different N has the equal value of the $I_{BP}$.

**BPR structure**

Our IVC show the thin structure in the BPR. Particularly, for stack with 11 IJJ at $\alpha$ = 1, $\beta$ = 0.2 and periodic boundary conditions we find 5 intervals in the BPR. The origin of this structure is still open. We consider that it is a manifestation of the mixed states of the rotating junctions and plasma oscillations. One of these intervals demonstrates an interesting behavior: the noise in current does not affect the IVC in wide region of noise amplitude variation.

**Conclusions**

In conclusion, we stress that the BPR in the IVC "naturally" follows from the solution of the system of the dynamical equations for the phase difference for the stack of IJJ. In the breakpoint region the plasma mode is a stationary solution of the system and this fact might be used in some applications, particularly, in high frequency devices such as THz oscillators and mixers. The detailed study of the breakpoint current and breakpoint region width gives a new opportunity for the investigation of the properties of IJJ and develop new methods for the determination of the parameters of IJJ and diagnostic of IJJ in the stacks.

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**References**