Equivalent circuit model for high-T_c superconducting flux flow transistor with a dual-gate structure

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We have fabricated dual-gate superconducting flux flow transistor (DGSFFT) with a micro-scale structure from epitaxial superconducting thin films by photolithography. We were performed the simulation for the voltage modulation by varying the penetration depth as a function of the dual-gate currents. This model showed the dependence of the critical current density on the spatial distribution of an applied magnetic field induced by dual-gate currents. The *I-V* curves of DGSFFT with a micro-scale channel from the simulation were in agreement with the measured curves in the flux creep regime.

The channel of superconducting flux flow transistor (SFFT) is classified into the Josephson junctions [1] and the weak-links [2] depending on the fabrication method. The Josephson junction flux flow transistors are more complex and more difficult to fabricate than weak-links flux flow transistors. Following the initial work on high-T_c thin film by Martens *et al*. [2], many groups have made SFFTs and have studied its properties by a simulation [3,4]. In this paper the current-voltage curves in the DGSFFT (dual-gate superconducting flux flow transistor) with a micro-scale channel were simulated varying the penetration depth as a function of the dual-gate currents. This paper proposes *I-V* characteristic simulation using a computational method to analyze the DGSFFT. We applied the Biot-Savart's laws and the Kim-Anderson's model and derived the mean-field description by Bernstein *et al.* from this simulation. The induced output voltage as a function of gate current transporting the dual-gate line could be computed from the derived numerical model. The calculated values were compared in relation to the serial flow of the vortices in the micro-scale channel.

MODEL OF THE DGSFFT

We fabricated the DGSFFT with a micro-scale channel and constructed an analytical model. The DGSFFT having a micro-scale channel is composed of dual-gate structure and two serial channels biased with a drain current I_d as shown in Figure 1 (a). Figure 1 (b) shows the equivalent model of a serial DGSFFT. The nucleation and the motion of Abrikosov vortices in the channel can be generated and controlled by a magnetic field induced by the dual-gate currents which flow near the channel. Figure 1 (c) shows the schematic diagram of the SFFT with the micro-scale channel. Figure 1 (d) shows the optical microscope image of the SFFT with the micro-bridge.

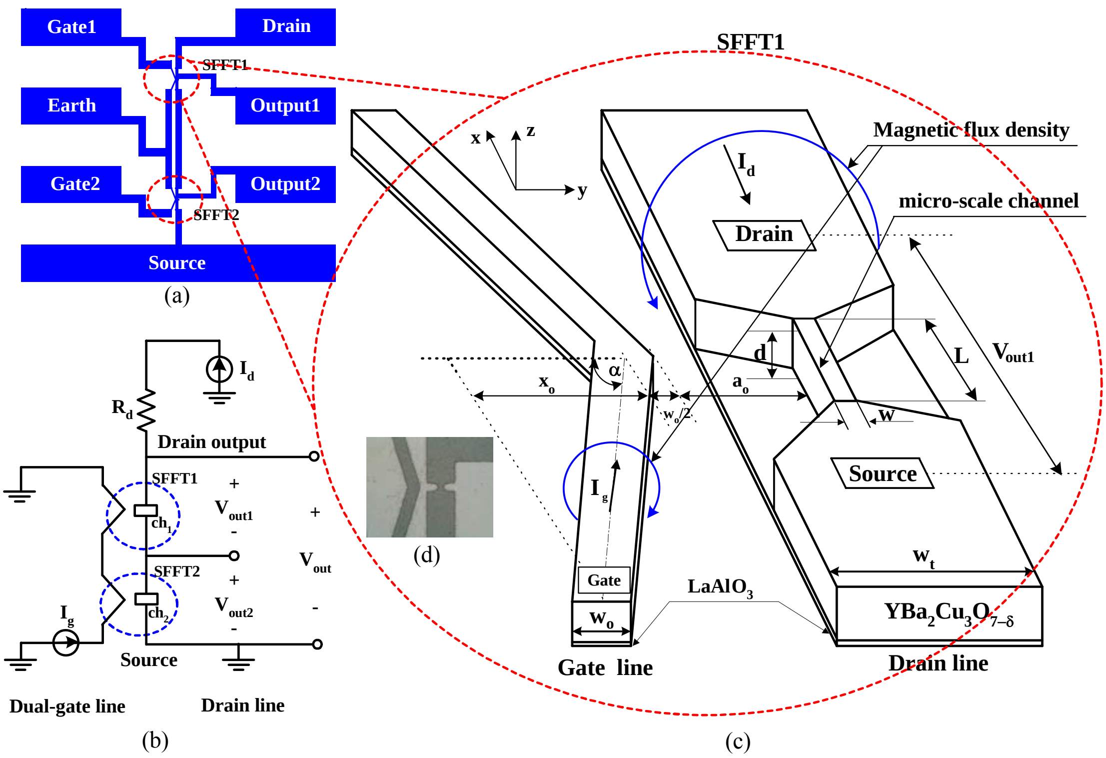

Figure 1 Structure of the DGSFFT with a micro-scale channel. (a) Mask pattern of the DGSFFT. (b) The model of a serial DGSFFT. (c) Schematic of the SFFT with the micro-scale channel. (d) Optical microscope image of the micro-bridge SFFT

The amplitude of the voltage V_{out} induced by the vortex and anti-vortex motion at the micro-bridge terminals can be given as

$$V_{out} = \frac{\Delta\Phi}{\Delta t} = B\frac{\Delta S}{\Delta t} = B\, v(w/2)\, L = \frac{N_{vortex}}{S}\phi_0\, v(w/2)\, L = n(w/2)\, v(w/2)\, \phi_0\, L \quad , \tag{1}$$

where Φ, t, B, S and N_{vortex} are the flux in the channel, time, the magnetic field, the channel area and the number of vortices, respectively. $n(w/2)$ is the mean surface density of the moving vortices or anti-vortices and L is the length of the micro-scale channel. $v(w/2)$ and ϕ_0 are the average vortex velocity and the absolute value of the flux quantum carried by each vortex and anti-vortex, respectively.

If the induced voltage from the ch_1 is equal to voltage of the ch_2 in the equilibrium state, the output voltage induced at the output drain terminals can be written as follows:

$$V_{out} = V_{out1} + V_{out2} = 2\left\{\frac{\mu_0\, L\, k_B\, T\, \delta \exp^{-(E_P/k_B T)}}{d\,\hbar}\right\} \times \sinh\left(\frac{I_d}{w k_B T/(\delta\,\phi_0)}\right)$$

$$\times\left\{I_d - \left[I_{cr} + \frac{\sin\alpha\, I_g}{\pi}\left\langle \frac{1}{w_g}\sin\left(\tan^{-1}\frac{x_0\tan\alpha}{w_g}\right) - \frac{1}{w_g + w}\right.\right.\right. \quad , \quad \text{for} \quad I_d \geq I_{cr}, \qquad (2a)$$

$$\left.\left.\left.\times \sin\left(\tan^{-1}\frac{x_0\tan\alpha}{w_g + w}\right)\right\rangle \times \left(\frac{\sqrt{2}\lambda\,\sinh\left(d/\sqrt{2}\lambda\right)}{1+\cosh\left(d/\sqrt{2}\lambda\right)} + \frac{(k-2)d}{2}\right)\right]\right\}$$

$$V_{out} = V_{out1} + V_{out2} = 0, \qquad \text{for} \quad I_d < I_{cr}, \qquad (2b)$$

where x_0 is a distance of a straight line from the central line of the gate line to both side edge of gate line and α is an angle from the center of gate line. w and λ are the width of the channel and the penetration depth, respectively. w_0 is the width of the gate line. a_0 is the spacing between the gate line and the channel edge of the drain line. d and I_{cr} are the thickness of the micro-scale channel formed by wet etching method and the critical current, respectively. δ and T are pinning potential range and the temperature, respectively. k and I_{cro} are the fitting constant and the initial critical current of the case without applied field, respectively. $w_g = (x_0 + w_0/2 + a_0)$, E_p and k_B are the total distance between the gate line and the drain line, the individual vortex activation energy and the Boltzman's constant, respectively. Then, the penetration depth λ can be expressed as follows [3]:

$$\{\mu_0\, I_{cro}\} \Big/ \left\{4d\left[\frac{1}{2} + \frac{\lambda}{d}\left(\frac{\sqrt{2}\sinh(d/\sqrt{2}\lambda)}{1+\cosh(d/\sqrt{2}\lambda)}\right)\right]\right\} = \left\{\left[\phi_0/(4\pi\lambda^2)\right]\Big/\sqrt{\frac{\pi w}{4d}}\right\} \times \ln\left(\frac{\lambda}{\xi}\right), \qquad (3)$$

where the penetration depth λ can be expressed as a function of I_{cro}, d, ξ, and w. If the micro-bridge geometrical dimensions, critical current, and coherence length are given, it is possible to compute λ from Eq. (3).

RESULTS AND DISCUSSION

We have fabricated the DGSFFT with the thickness 350 nm and the channel width 10 μm, and the channel length 5 μm using photolithography process and measured the *I-V* characteristics. The $YBa_2Cu_3O_{7-\delta}$ films were wet etched by 0.67% phosphoric acid (H_3PO_4). The most important steps of the patterning process are the etching time for aqueous solution of phosphoric acid. Figure 2 shows the measured and the calculated *I-V* characteristics of DGSFFT with the micro-bridge that plotted from Eqs. (2-3). From the *I-V* characteristics curves, three regimes such as thermally activated flux flow (TAFF), the flux creep mode and the flux flow mode were reflected to explain the measured and calculated current-voltage curves. As a simulation result, it showed that the total voltages induced from the ch_1 and ch_2 increased more than the voltages induced from the ch_1 in the equilibrium state. The simulation results of the current-voltage characteristics are similar to the measured results.

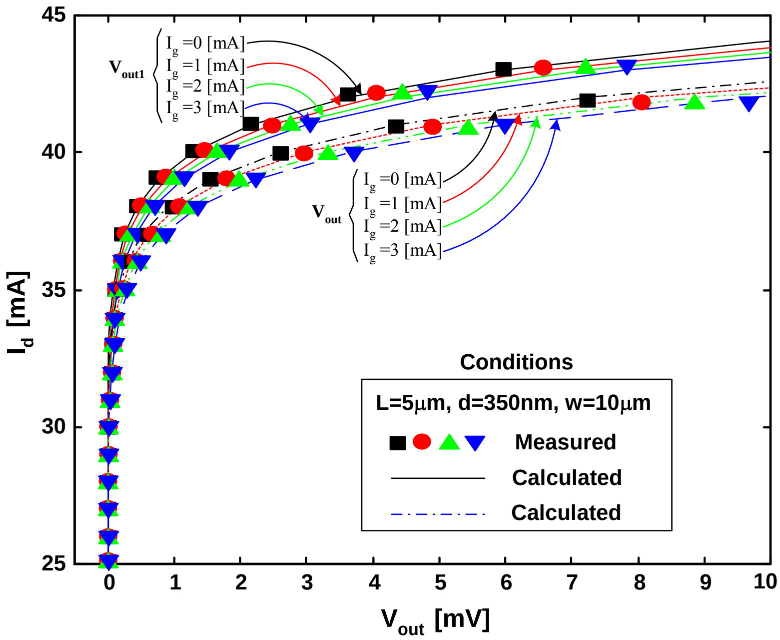

Figure 2 Measured and calculated *I-V* characteristics curves of the output voltage as a function of the dual-gate current of DGSFFT with the micro-bridge at 77K

CONCLUSIONS

We have tried to determine the *I-V* characteristic equation that was modified in proportion to the length, the width and thickness of the micro-scale channel, and a distance between the drain line and the gate line. We proposed analytical model that was composed of the DGSFFT with the micro-scale channel. We worked the simulation to analyze *I-V* characteristics of DGSFFT having a micro-bridge using the computational method. When compared to the calculated and measured values, the induced voltage agreed alike in the DGSFFT with a micro-bridge in the flux creep regime. This model is suitable for prediction of the *I-V* characteristics of a DGSFFT with a micro-scale channel in the flux creep regime.

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