

Pulse Current Response of High- T_c Superconducting Vortex Flow TransistorsY. Doda,^{1,2} T. Kiwa,^{1,2} I. Kawayama,^{1,2,*} H. Murakamia,¹ and M. Tonouchi^{1,2}¹*Research Center for Superconductor Photonics,**Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan*²*CREST, Japan Science and Technology Corporation (JST)*

The properties of superconducting vortex flow transistor (SVFT), which consist of a vortex flow channel and a control line for applying a magnetic field, are diagnosed by using a current pulses train method. The time-domain waveforms of the vortex flow voltage along the channel were measured using the current pulses train with the pulse width of 5 ns as input signals. The fast response of the flow voltage suggests that the heating effect is negligible and the effect of the magnetic field generated by the control line was dominant in our measurement. The vortex flow speed was estimated from the ratio of the flux flow voltage to the control current, and was found to be 8.6×10^4 m/s. We also estimated the pinning energy E_p from the vortex flow speed, and found that the value of E_p is around 8.6 meV for our device, which can be easily excited by a conventional Ti:sapphire femtosecond laser.

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I. INTRODUCTION

Since the discovery of high- T_c superconductors (HTSCs), various kinds of HTSC devices, which exploit vortices flow in superconducting thin film strips or in Josephson junctions, have been proposed and developed to realize high frequency and high-speed devices. Among these HTSC devices, superconducting vortex flow transistors (SVFTs) are expected to show the promising performance, which exceed the performance of conventional semiconductor devices [1, 2].

The SVFTs typically consist of a vortex flow channel and a control line for applying a magnetic field. Abrikosov vortices are generated in the channel and the density of vortices are controlled by applied magnetic field via control current I_{co} . The flow voltage V_f along the channel is induced by applying the bias current I_B in the channel, since Lorentz force which drives vortices is proportional to I_B . Thus V_f can be controlled by I_{co} and I_B . Martens *et al.* [3] demonstrated that the HTSC SVFTs could operate at the frequency of 93 GHz. However, few groups, in our knowledge, have achieved the device operation at such a high frequency. Since the mean vortex flow speed in the channel, which limits the maximum frequency of the device operation, is strongly affected by vortex pinning force in the channel, the maximum frequency of the device depends on the quality of the films.

Recently, we demonstrated that the vortex flow speed increased with irradiating the laser pulses to the channel [4]. The experimental results suggest that V_f can be controlled by the laser pulses and the SVFTs are one of promising devices for optical interface of single flux quantum (SFQ) logic devices. However, since DC current was applied to the control

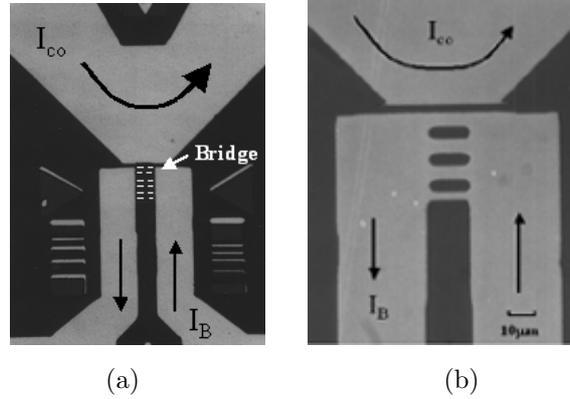


FIG. 1: (a) A micrograph of the superconducting flux flow transistor (SVFT) composed of four-vortex flow bridge separated by holes and a control line located $2 \mu\text{m}$ from the edge of the channel. (b) the micrograph of the active part of the device.

line in order to measure the properties of the device, the Joule heating from the contact resistance cannot be neglected and makes it difficult to estimate vortex flow speeds.

In this work, we applied the current pulses train $I_{co}(t)$ to the control line, and measured the flux flow voltage $V_f(t)$ in time-domain. Thus, we expected that the vortex flow speed and related properties of the device could be estimated without the heating effect.

II. EXPERIMENTAL DETAILS

A c -axis oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin film with the thickness of 200 nm prepared on an MgO(100) substrate are used. The film was covered by gold layer with the thickness of 45 nm, which was deposited by RF sputtering. The YBCO thin film was patterned into the SVFT device structure by a conventional photolithographic technique and an Ar ion dry etching process. Fig. 1(a) shows the micrograph of the active region of the SVFT device. The vortex flow channel consists of four superconducting strips with $3\text{-}\mu\text{m}$ -width and $10\text{-}\mu\text{m}$ -length. The spaces between the strips are $3 \mu\text{m}$ (Shown in Fig. 1(b)). After the patterning, the gold layer on the flow channel was removed and then the thickness of the channel was reduced to about 60 nm by the same etching process in order to reduce the pinning force in the channel. A control line with the width of $650 \mu\text{m}$ is located in $2 \mu\text{m}$ from the edge of the channel.

Fig. 2 shows schematic diagram of the pulse current measurement system used in this study. The electric properties of both of the control line and the channel was measured by a four point-contacts method. The temperature was kept at 20 K during the experiments. A squared voltage pulses train was applied to the series circuit of the control line and a metal-coated resistor of 100Ω using the digital oscillator. Since the resistance of the resistor is large enough compared to the contact resistance between the gold layer and the

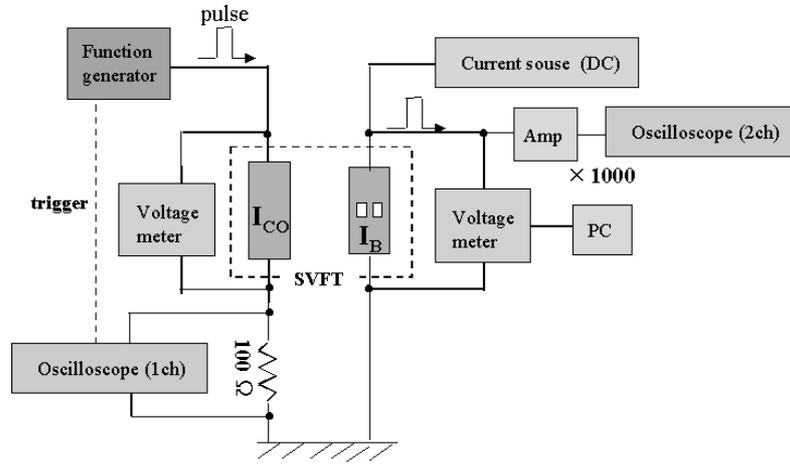


FIG. 2: Schematic diagram of a current pulses train measurement system for the SVFTs.

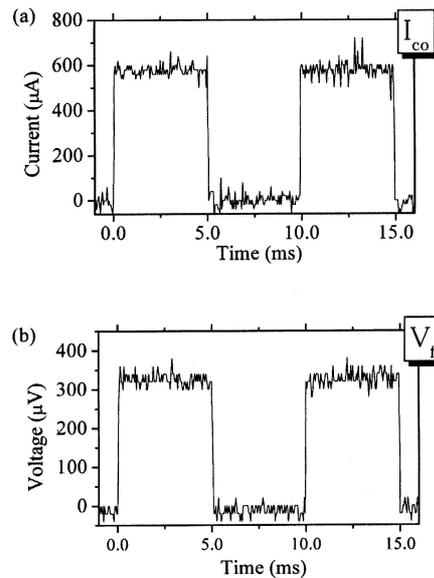


FIG. 3: The time-domain waveform of (a) the incident pulse current $I_{co}(t)$ and the (b) the vortex flow voltage $V_f(t)$ of the SVFT. The pulse width of incident current are 5 ms.

YBCO thin film, the quantitative amplitude of the current through the control line can be estimated from the voltage induced in the resistor, which was monitored in time-domain by an oscilloscope. We confirmed that the control line was in the superconducting state during the experiment by monitoring the voltage of the control line.

III. RESULTS AND DISCUSSION

The time-domain waveform of the incident pulse current to the control line $I_{co}(t)$ and the flow voltage along the channel $V_f(t)$ are shown in Fig. 3(a) and (b), respectively. The width of the pulse current is 5.0 ms, and the peak amplitude of $I_{co}(t)$ is around 600 μA . The time resolution of acquired data was 50 μs .

The response of $V_f(t)$ follows the incident pulse current $I_{co}(t)$ without time delay in this time resolution. This fact suggests that a thermal effect of control line is negligible and the effect of the magnetic field is dominant in our device.

The vortex flow speed v was calculated from the measured current response using the following method. The V_f is related to the vortex flow velocity v , and given by [5],

$$v(\text{m/s}) = \frac{V_f}{Bd} = \frac{1}{d\alpha} \frac{V_f}{I_{co}}, \quad (1)$$

where α is the geometrical factor of the device and is calculated to be 16700 for our device. B is the flux density induced in the channel, and d is the length of the channel. Therefore the flux flow speed v is proportional to the slope of V_f and I_{co} ($\Delta V_f/\Delta I_{co}$). We observed the flux flow voltage V_f that are 294 μV and 356 μV , when the current pulses of $I_{co}=530 \mu\text{A}$ and 640 μA were, respectively, applied to the control line with the pulse width of 500 ms. The $\Delta V_f/\Delta I_{co}$ was calculated from these values, and was 0.563. The vortex flow speed of our device is estimated to be approximately 8.6×10^4 m/s by substitution of the calculated value of $\Delta V_f/\Delta I_{co}$ for Eq. (1). The minimum response time of the SVFTs can be calculated as l/v , l is the channel width of 12 μm , and was 140 ps for our device. It corresponds 7.2 GHz of operation frequency.

The vortex flow speed of our device was one order in magnitude lower than the vortex flow speed of 5×10^5 m/s at 77 K for YBCO thin film device and 3×10^6 m/s at 17 K for NdCeCuO thin film device, which were estimated by Miyahara *et al.* using DC current measurement [6]. The differences may be caused by the quality of the thin films, because the flow speed strongly depends on the defects and dislocations which act as pinning sites. We estimated pinning energy and it can be written as [7],

$$V_f = 2v_{Lo}e^{-(e_p/k_B T)} \sinh\left(\frac{W}{k_B T}\right), \quad (2)$$

and

$$W \approx \frac{I_b \delta \phi_0}{w},$$

where I_b ($= 40 \mu\text{A}$) is the current through the channel. k_B and ϕ_0 are Boltzman's constant and a flux quantum, respectively. w is the width of the channel. $V_{Lo} = 10^6$ m/s and $\delta = 100$ nm are the maximum vortex speed and the pinning potential range at near the critical temperature. The value of the pinning energy was calculated to be around 8.6 meV by applying the value of the vortex flow speed to Eq. (2). This result indicated that laser

pulses produced by a conventional Ti:sapphire femtosecond laser with photon energy of 1.54 eV can easily release the flux pinning. The value of E_p was also enough to excite the vortex by introducing the laser signals with the wavelength of 1.55 μm and the photon energy of 800 meV, which are widely used in the field of optical communication systems (C-band). This fact implies that a HTSC SVFT is one of the promising devices for optical interconnections between SFQ circuits and the other devices such as semiconductor devices, optical fiber systems, and SFQ devices itself.

IV. CONCLUSION

The properties of SVFTs made of YBCO thin films were observed by means of the current pulses train measurement at 20 K with the pulse width of 5 ns. The measurement of time-domain waveform of $V_f(t)$ and $I_{co}(t)$ suggests that a thermal effect can be negligible and the effect of the magnetic field is dominant. The vortex flow velocity driven by the pulse current signal was estimated to be around 8.6×10^4 m/s, and pinning energy in the channel was estimated to be around 8.6 meV. Now we are constructing the measurement system that combined the pulse current measurement and the irradiation system of ultrafast optical pulses.

Acknowledgments

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