Quasi-particle Injection Device for the Interface between Superconductor and Semiconductor

Hidehiro Shiga and Yoichi Okabe

Abstract— **We have fabricated an injection type 3-terminal device for interface between superconductor and semiconductor circuit using high temperature superconductor. When quasi-particles are injected from the Au electrode to $YBa_2Cu_3O_{7-x}$ (YBCO) bridge, the superconductivity of the bridge area is weakened and I_c of the bridge decreases. Therefore, we can easily make the bridge in resistive state by injecting sufficient amount of current I_{inj}. The length, width, and thickness of the bridge are 20 μm, 10 μm, and 100 nm, respectively. The Au–YBCO contact area is 200 μm^2. When the bridge became in resistive state, the resistance was about 100 Ω. The current gain $|\Delta I_c / \Delta I_{inj}|$ was as high as 9. However, the contact resistance was about 17 Ω, which is 200 times as large as the required value for the operation as an interface device. This shortcoming might be overcome by appropriate annealing.**

Keywords— **YBCO, quasi-particle injection, interface, amplifier.**

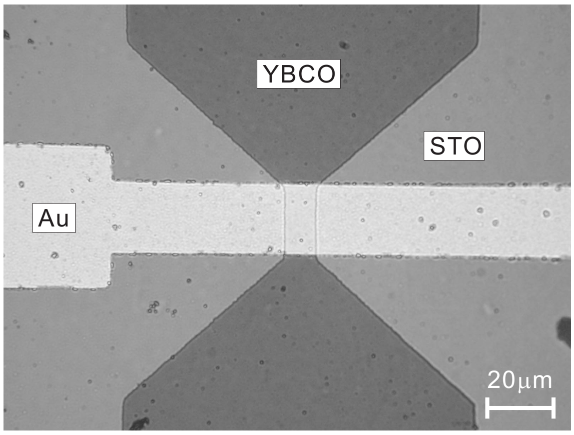

Fig. 1. Microscopic photograph of the device.

I. Introduction

Within a few years, superconductor computer that can calculate faster than the present supercomputer would be realized and become in use. Then it is natural that hybrid computer systems that consists of superconductor and semiconductor logic circuits will be developed. However, one of the biggest problems for developing hybrid computer is the difference of the operation voltage. Semiconductor logic circuits are operated with the voltage larger than 1 V, while a superconducting quantum interference device (SQUID) can generate only 1 mV or so. This means that we have to amplify the voltage by a factor of about 1000 when we transfer a signal from superconductor to semiconductor.

As this kind of amplifier, SQUIDs connected in series have been proposed [1], but these SQUIDs generate only a few tens of mV and another amplifier raises the voltage at the next stage, to make sufficient voltage for the semiconductor circuit. This system is too large as an interface device, considering that the system is needed for each signal line from superconductor to semiconductor.

In order to overcome this drawback, we decided to fabricate quasi-particle injection device with high temperature superconductor (HTS). The quasi-particle injection device is constructed with a superconductor bridge and the quasi-particles injection electrode (gate) located over the bridge. By injecting quasi-particles from the gate to the bridge, I_c of the bridge is suppressed. Therefore, if proper value of bias current is previously applied to the bridge and then quasi-particles are injected, the superconductivity of the bridge area would be lost and some resistance would appear. Because the resistance is determined by the bridge length, we can obtain any voltage by adjusting it.

HTS quasi-particle injection devices have already been fabricated and investigated [2]-[4], as well as low temperature superconductor (LTS) devices [5], but most of them have an insulator layer between the injection electrode (gate) and the YBCO bridge. However, in order to inject large current with the small voltage generated by a SQUID, the resistance between the gate and the bridge must be as small as possible. Therefore, we fabricated an injection device without an insulator layer.

II. Fabrication Method

The fabrication method of the interface device is as follows:

1. Deposit $YBa_2Cu_3O_{7-x}$ (YBCO) film on $SrTiO_3$ substrate utilizing the pulsed laser deposition method. The thickness of the YBCO film was 100 nm. The T_c was about 85 K.
2. Make bridge pattern by lithography and Ar beam etching.
3. Make Au electrode pattern by lithography and lift-off. The thickness of the Au film is 40 nm
4. Anneal the substrate at 500 °C in atmospheric pressure O_2 for 1 h to reduce the Au–YBCO contact resistance.

The microscopic photograph of the fabricated device is shown in Fig.1. The bridge length and the width are 20 μm and 10 μm, respectively.

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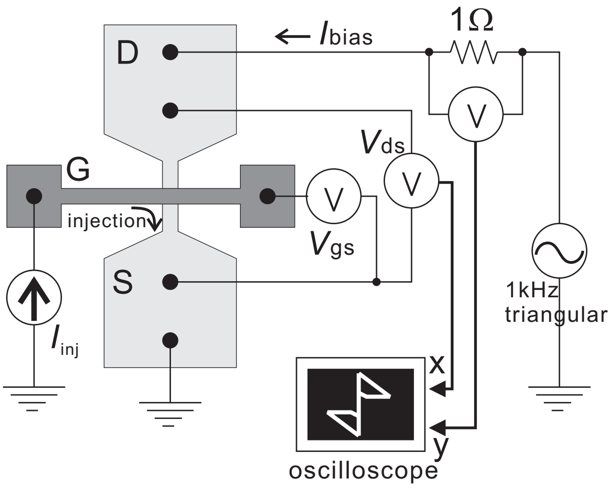


Fig. 2. Measurement system.

III. Measurement

A. System

The characteristics of the device was measured with the system shown in Fig.2. 1 kHz triangular wave was applied to the drain electrode as the bias current $I_{\rm bias}$. The voltage $V_{\rm ds}$was measured with four probe method. The gate has 2 pads: one for quasi-particles injection, the other for voltage measurement.

B. Temperature dependence

First, we measured the device characteristics without quasi-particles injection, that is, $I_{\rm inj} = 0$ mA.

In Fig.3, the temperature dependence of the device characteristics are shown. The $I_{\rm bias}$–$V_{\rm ds}$ characteristics measured at the temperature of 10 K, 30 K, and 50 K are shown in Fig.3-(a). The $I_{\rm c}$–temperature characteristics are shown in Fig.3-(b).

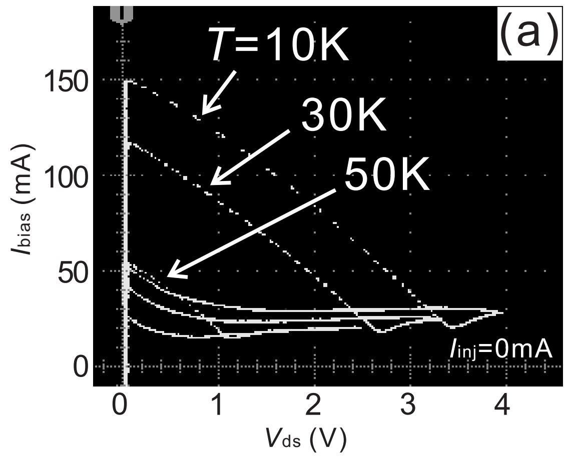
C. Injection dependence

Next, we fixed the temperature to 10 K and injected quasi-particles from the Au electrode to the YBCO bridge.

In Fig.4, the characteristics when the injection current $I_{\rm inj}$ was applied are shown. The $I_{\rm bias}$–$V_{\rm ds}$ characteristics are shown in Fig.4-(a). It can be understood from this figure that when $I_{\rm inj}$ was increased from 5 mA to 10 mA, for example, $I_{\rm c}$ of the bridge dramatically decreased from 127 mA to 82 mA. The current gain $|\mathit{\Delta} I_{\rm c}\ /\ \mathit{\Delta} I_{\rm inj}|$ at this point is about 9. More detailed data of the $I_{\rm c}$–$I_{\rm inj}$ characteristics are shown in Fig.4-(b). In the right half area ($I_{\rm inj} > 0$), the maximum current gain is about 9. On the other hand, in the left half area ($I_{\rm inj} < 0$), the slope is steeper and the gain reached as high as 12.

D. Contact resistance

Then we measured the Au–YBCO contact resistance. When $I_{\rm inj} = 12$ mA, the gate voltage $V_{\rm g}$ rose to 200 mV. Therefore, the contact resistance can be estimated to be about 17 Ω.



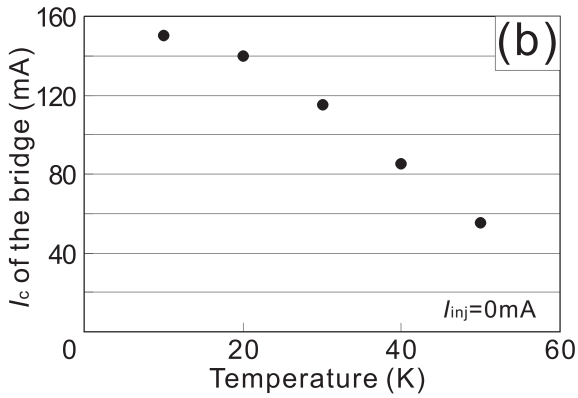


Fig. 3. Temperature dependence of the characteristics. (a) The $I_{\rm bias}$–$V_{\rm ds}$ characteristics at 10 K, 30 K, and 50 K. (b) The $I_{\rm c}$–temperature characteristics.

IV. Discussion

A. $I_{\rm bias}$–$V_{\rm ds}$ characteristics

The $I_{\rm bias}$–$V_{\rm ds}$ characteristics are partly explained by the simple model shown in Fig.5-(a). First, the switch parallel to the resistance R_2 is short circuited. The variable voltage supply increases the voltage v. If the switch becomes open when v=v_0, the operation point ($V_{\rm ds}$,$I_{\rm bias}$) jumps from (0, $\frac{v_0}{R_1}$) to ($\frac{R_2}{R_1+R_2}v_0$, $\frac{v_0}{R_1+R_2}$). This jump corresponds to the change from superconductive state to resistive state. The operation point after the jump is on the line y=$\frac{1}{R_2}x$ regardless of the value of v_0. Then, if the voltage decreases from v_0, which is the case of the actual measurement, the point moves along the line toward (0, 0).

However, the characteristics shown in Fig.3-(a) and Fig.4-(a) do not exactly agree with Fig.5-(b). After the jump, the operation point moves almost horizontally and finally, when $V_{\rm bias}$ is near 0, $I_{\rm bias}$ even increases.

In Fig.5-(c), the characteristics of the injection device fabricated with LTS[5] are shown. In the case of this device, the $I_{\rm bias}$–$V_{\rm ds}$ curve when the bridge is in resistive state is almost the same as that of constant resistance (roughly on the line I=$\frac{1}{1000}V$). This means that the operation principles of HTS device and LTS device are different.

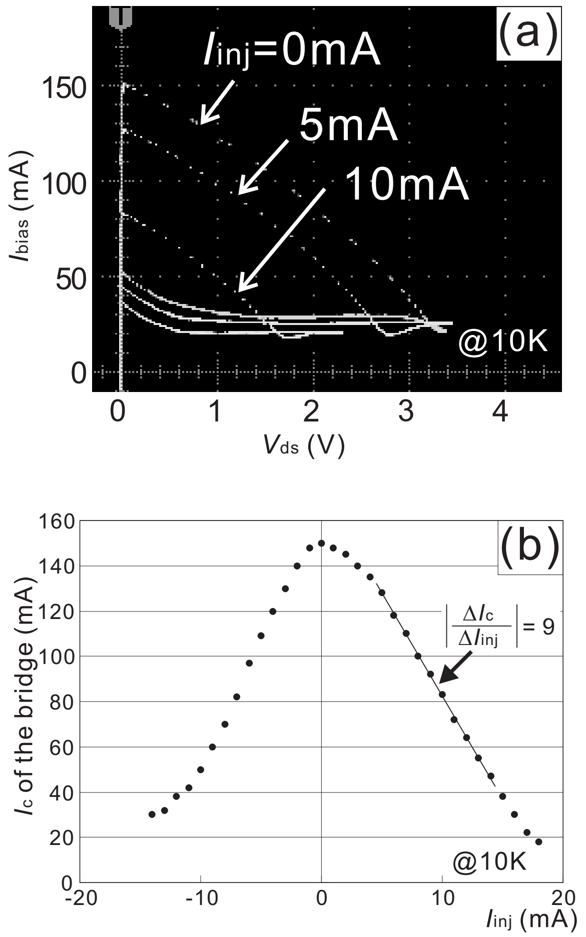


Fig. 4. Injection current dependence of the characteristics. (a) The I_{bias}–V_{ds} characteristics at I_{inj}= 0mA, 5mA, and 10mA. (b) The I_c–I_{inj} characteristics.

B. Contact resistance

From the result shown in Fig.4-(b), we estimated that more than 10 mA of current injection would be enough for device switching, because I_c can be suppressed to half the value of the maximum, i.e. from 150 mA to about 80 mA. Therefore, in order to operate this device with the voltage generated by a SQUID (~1 mV), the Au–YBCO contact resistance must be lower than 1 mV / 10 mA = 0.1 Ω. This value is about 1/200 of the one we have obtained, 17 Ω, as referred in the previous section. However, it is not impossible to realize as low resistance as 0.1 Ω because: The Au–YBCO contact area is 200 μm^2, thus the surface resistivity is 17 Ω×200 μm^2 = 3.4×10^{-5} Ω·cm^2. According to the previous report, contact surface resistivity of less than 10^{-11} Ω·cm^2 can be obtained by appropriate annealing[6]. If we improve the annealing conditions and obtain low contact resistance, the practical operation of this interface device becomes much realistic, though this reduction of the resistance might cause some changes on the device characteristics.

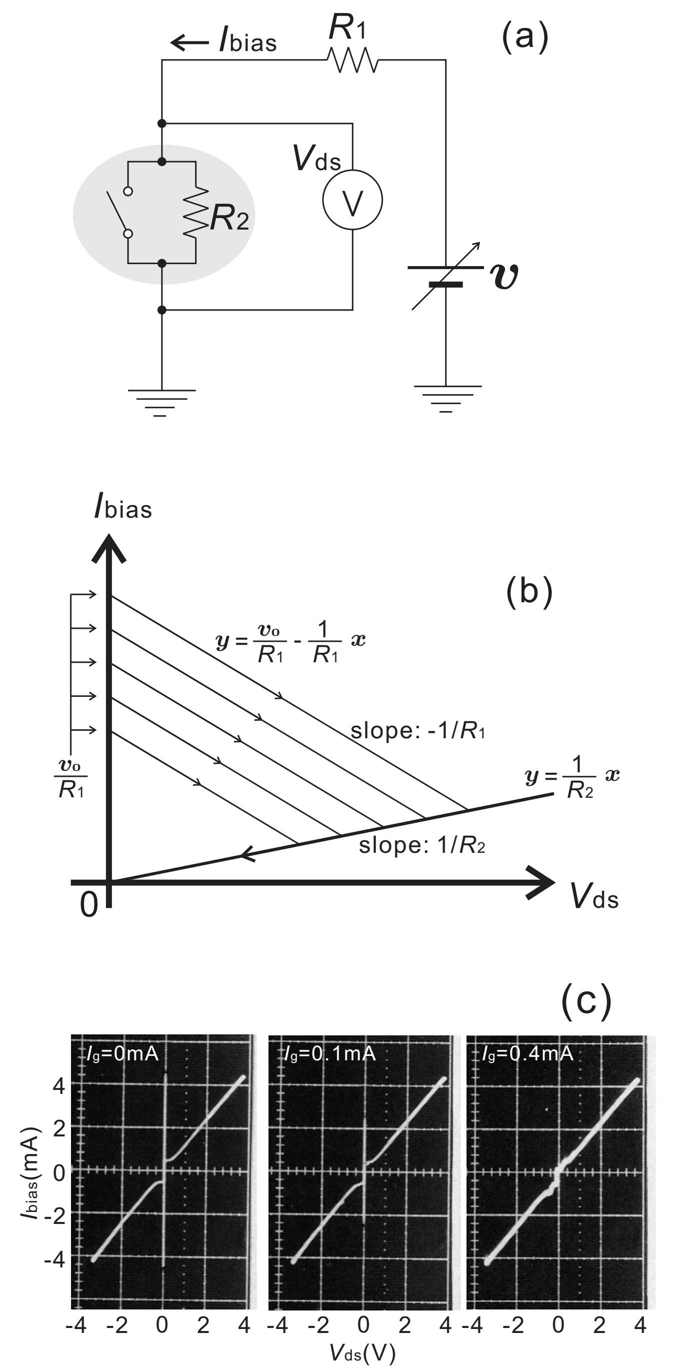


Fig. 5. (a)A model circuit. (b)The I_{bias}–V_{ds} characteristics of this model. $\frac{v_0}{R_1}$ corresponds to I_c. (c)The I_{bias}–V_{ds} characteristics of LTS device[5].

V. Conclusion

We have fabricated an injection type 3-terminal device aiming at the interface between superconductor and semiconductor circuit. By the injection of quasi-particles into YBCO bridge, the current gain of more than 9 was obtained at 10 K. However, in order to operate this device with the voltage generated by a SQUID, it is necessary to reduce the Au–YBCO contact resistance to 1/200 of the one obtained this time.

References

[1] T.Abe, K.Kosuge, and N.Yoshikawa, “Design of a SQUID amplifier for RSFQ/CMOS hybrid systems”, *Extended Abstracts (The 47th Spring Meeting, 2000); The Japan Society of Applied Physics and Related Societies*, No.1, pp.265, 28a-G-9, 2000.

[2] T.Kobayashi, K.Hashimoto, U.Kabasawa, and M.Tonouhi, “Three terminal YBaCuO Josephson device with quasi-particle injection gate”, *IEEE Trans. Magn.* **25**, pp.927-930, 1989.

[3] Y.M.Boguslavskij, K.Joosse, A.G.Sivakov, F.J.G.Roesthuis, G.J.Gerritsma, and H.Rogalla, “Quasiparticle injection effects in $YBa_2Cu_3O_x$-based planar structures at high operating temperatures”, *Physica C* **220**, pp.195-202, 1994.

[4] Q.Wang and I.Iguchi, “Effective suppression and enhancement of critical current in a nonequilibrium $YBa_2Cu_3O_{7-x}$ film due to tunnel injection of quasiparticles”, *Physica C* **228**, pp.393-400, 1994.

[5] Y.Okabe, P.Anprung, and K.Fukuoka, “Superconductive controlled weak-links”, *Jpn.J.App.Phys.* **25** No.9, pp.1342-1347, 1986.

[6] J.W.Ekin, T.M.Larson, N.F.Bergren, A.J.Nelson, A.B.Swartzlander, L.L.Kazmerski, et al., “High T_c superconductor/noble-metal contacts with surface resistivities in the $10^{-10}\Omega\mathrm{cm}^2$ range”, *Appl. Phys. Lett.* **52**, pp.1819-1821, 1988.