# High Tc superconducting electronics

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# High Tc superconducting electronics

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## 1) Intrinsic Josephson Effect

It is well known that the fundamental device of superconducting electronics is Josephson tunnel junctions. But Josephson tunnel junctions composed of high Tc superconductors are not yet achieved artificially. However it has been known recently that the crystal structures of high Tc superconductors compose itself Josephson junctions intrinsically. The observed I-V characteristics of $Bi_2Sr_2CaCu_2O_8$ single crystals are explained by intrinsic Josephson effect[1][2]. When the current flowing to the c-axis direction of the small $Bi_2Sr_2CaCu_2O_8$ single crystal is applied, the I-V curves are similar to that of Josephson tunneling junctions.

Also sharp absorptions of GHz range radiation are observed with $Bi_2Sr_2CaCu_2O_8$ single crystals in several Tesla field parallel to the c-axis[3][4]. The microwave absorption phenomenon is explained by Josephson plasma excitations in cuprate single crystals[5].

Tamasaku et al. measured the reflectivity for THz region electro-magnetic waves with c-axis polarization using high-quality single crystals of $La_{2-x}Sr_xCuO_4$[a] (LSCO)[6]. They found that the LSCO single crystals are high-pass filters with a characteristic frequency in the THz region. To explain the experimental results, Tachiki et al. proposed a new theory of low-frequency plasma excitations propagating an ab plane in high-quality single crystals of highly anisotropy cuprate superconductors[5]. The theory is based on the two-dimensional nature of the LSCO for which carriers are almost confined in the $CuO_2$ layers and other layers remain semiconductive. The two-dimensional nature of the electronic state and a large dielectric constant along the c-axis reduce the plasma frequency $\omega_p = c_s / \lambda_c \simeq 5THz$, where $c_s$ is the velocity of a plasma wave and $\lambda_c$ is the London penetration depth along the c-axis. As the quantum energy ($\hbar\omega_p \simeq$ meV) is smaller than the superconductive gap energy ($E_g \simeq$ 10meV), excited plasma propagates without damping in the superconductiv state.

The same situation occurs for Josephson plasma frequency $\omega_J = c_J / \lambda_c \simeq 50 \sim 500GHz$ in Nb Josephson junctions[7]. In Table I, the characteristic values of cuprate superconductors are compared with those of Josephson junctions. From the table, we observe that $\omega_p$ is one or two orders of magnitude higher than $\omega_J$. Also the penetration depth along the c-axis of a cuprate superconductor is same orders of magnitude smaller than that of Josephson junctions. Using the high $\omega_p$ and small $\lambda_c$ of the cuprate superconductors, we propose new high-gain switching gates with sizes of the order of $\lambda_c$ and the minimum switching time $\tau_s \simeq 1/\omega_p$.

As Josephson plasma frequency determines the operating frequency of Josephson devices, it may be possible to achieve new devices which operates at about two orders of magnitude higher frequency than existing Josephson devices.

The value of plasma frequency $\omega_p$ is one or two orders of magnitude higher than that of $\omega_J$ of junction because of small penetration depth $\lambda_J$ of single crystals compared to $\lambda_c$ of junctions. It is shown in Table I that the difference of $\lambda_c$ and $\lambda_J$ caused by that of the critical current density $j_0^s$ and $j_0^J$. The values of $2\lambda_c$ and $2\lambda_J$ are about the size of one flux quantum. As these sizes determine the minimum size of switching gates and memory cells in superconducting devices, the size of single crystal devices is about two orders of magnitude smaller than that of existing Nb Josephson devices.

| | Cuprate superconductor | Josephson junction |
|---|---|---|
| **Plasma frequency** | $\omega_p = c_s / \lambda_c \simeq 5THz$ (1) | $\omega_J = c_J / \lambda_J \simeq 500GHz$ (6) |
| **Velocity of waves** | $c_s = \left(\frac{1}{\varepsilon_J \varepsilon_0 \mu_0}\right)^{1/2} \simeq 0.2c$ (2) | $c_J = \left(\frac{t}{\varepsilon_J \varepsilon_0 \mu_0 (2\lambda_L + t)}\right)^{2} \simeq 30\mu m$ (7) |
| **Penetration depth** | $\lambda_c = \left(\frac{\Phi_0}{2\pi} \frac{1}{\mu_0 j_0^s c_0}\right) \leq 1\mu m$ (3) | $\lambda_J = \left(\frac{\Phi_0}{2\pi} \frac{1}{\mu_0 j_0^J (2\lambda_L + t)}\right) \simeq 30\mu m$ (8) |
| **Critical current density** | $j_0^s = \frac{\Phi_0}{2\pi} \frac{1}{\mu_0 \lambda_c^2 c_0} \simeq 10^{11} A/m$ (4) | $j_0^J = \frac{\Phi_0}{2\pi} \frac{1}{\mu_0 \lambda_J^2 (2\lambda_L + t)} \simeq 10^7 A/m^2$ (9) |
| **Size of a flux quantum** | $2\lambda_{ab} \cdot 2\lambda_c \simeq 0.2\mu m^2$ (5) | $2\lambda \cdot 2\lambda \simeq 20\mu m^2$ (10) |

Table I.

In Table I, plasma frequency, velocity of electromagnetic wave, penetration depth, critical current density, and size of a flux quantum are compared for a cuprate superconductor and a Josephson junction. The estimated values are derived for $La_{2-x}Sr_xCuO_4$ where $\lambda_{ab}$= 800A. $\lambda_c$ = 8000A, the interlayer spacing $c_0$ = 13.2 Å, and the dielectric constant $\varepsilon_s$ = 25 are used.[5] The value of $Bc1^s$ is derived using references[8] and[9] where $K = \ell n\frac{(\lambda_{ab}{}^2\lambda_c)^{1/3}}{(\xi_{ab}\xi_c)^{1/2}} + 0.5.$

## 2) Electronic Devices Using Intrinsic Josephson effect

We discuss signal amplification using a switching gate made of a Nb Josephson junction as shown in Fig.1A. The input flux signal $\Phi$ is applied to the switching gate using an input inductance L and the relationship of $\Phi = LI_I = \Phi_0$, where $\Phi_0$ is a flux quantum. The application $\Phi_0$ reduces the gate current $I_g$ to be zero because of the quantum effect of the gate as shown in Fig.1(B)[10]. In order to achieve signal amplifier, the output gate current $I_g$ should be larger than the input current $I_I$. From the relationships of $I_I = \Phi_0/L$ and $I_g > I_I$, we obtain the next requirement,

$LI_g > \Phi_0$ -------(1).

If we use the relations $I_g = j_0{}^J \ell w$ . and $L = \mu_0 \ell (2\lambda_L + t) / w$, the next requirement,

$\ell > \sqrt{2\pi}\lambda_J$ -------(2).

Then we conclude that the size of the amplifier gate should be larger than several $\lambda_J$, or the size of flux quantum $2\lambda_J \simeq 60\mu m$ .

In real amplifier circuits the full amount of output current $I_g$ can not be transferred to the input of a next amplifier. The maximum available current to the next input is 50% when the impedances are matched between the output and input terminals. The real requirement is then expressed as $I_g / 2 > I_I$ and eq.(2) is rewritten as $\ell > 2\sqrt{\pi}\lambda_J \simeq 100$ $\mu m$

The requirement of a flux quantum memory composed of loop inductance $L_m$ and a junction having a critical current $I_g$ is also expressed as $L_m I_g > \Phi$ , which means that the size of a memory cell should be larger than $\Phi_0$ as in the case of gates. As shown in Table I, the area of the flux quantum of cuprate single crystals is one or two orders of magnitude smaller than existing Nb Josephson junctions. If we use cuprate single crystals instead of Nb junctions, it is possible to achieve devices of which size is one or two orders of magnitude smaller than Nb junctions. We propose the gate model using a cuprate single crystal as shown in Fig.2(A). The discussion on the requirement to get amplifier gate with cuprate single crystals give us a qualitatively same result as

Nb Josephson junctions. The size of the gates should be larger than $2\lambda_c$ in the case of cuprate superconductors,[11)]

$$\ell > 2\lambda_c \text{ -------(3)}$$

The typical size of the single crystal gate is as follows, length $\ell$ and width w are both $\ell \simeq w \simeq 2\mu m$ , and hight $hight >> 2\lambda_{ab} \simeq 2\mu m$. The input current $I_i$ is applied to induce flux $\Phi = LI_i$. When applied flux $\Phi$ reaches to $B^5_{cl} \cdot \ell h$, a flux quantum chain is created as shown in Fig.2 (B), where $B^5_{cl}$ the lower critical field density of cuprate single crystals (Table I). If the gate current $I_g$ is applied to drive the flux quantum chain by Lorentz force, the flux quantum move quickly in the ab-plane which induces output voltage for c-axis direction. Such switching operation is qualitatively similar to existing Josephson gates[10)]. The switching time $\tau_s$ corresponds to the crossing time of a flux quantum in the gate $\tau_s \simeq \ell / c_s$ . If $\ell = 2\lambda_c$ we obtain $\tau_s \simeq 1/\omega_p \simeq 0.1ps$. It is possible to achieve the single crystal gate with switching time of sub. picosecond and size of about several $\mu m$.

From Table I, the peculiar features of existing Nb Josephson devices are recognized as follows.

(1) High frequency performances up to plasma frequency $\omega_J \cong$ 500GHz, and fast switching time

$$\tau_s \simeq 1/\omega_J \simeq 20ps,$$

(2) small device size $\simeq 4\lambda_J \lambda_L \simeq$ several $10\mu m^2$

The device size is mainly dependent on $\lambda_J$ and highly dense integrated circuits are achieved by smaller $\lambda_J$ . The switching time is determined by the time of one flux quantum across the gate length $\ell$ . Shorter crossing time gives faster operation of devices. Nb Josephson junctions are used for switching gates and memory cells and operate with switching time $\tau \cong 1/\omega_J$ of about 10 ps, which is faster enough operations compared to existing high speed semiconductor devices. However, the size of existing Josephson junction is about $2\lambda_J \leq 50 \sim 100\mu m$ , which is too larger than existing high speed CMOS devices with gate length of $0.8\mu m$[12)]. The Josephson devices are about two orders of magnitude larger than semiconductor devices and are no match for CMOS devices in fields of highly dense integrated circuit technology. The existing Josephson devices has big merits in high speed operation and low energy consumption or high sensitivity as sensors. But they have no chance to compete in the field of highly dense integrated circuit technology which needs quite small devices. Josephson penetration depth $\lambda_J \cong 30\mu m$ is too large to develop Josephson integrated circuits. As shown in Table I, the penetration depth $\lambda_c$ of a cuprate single crystal is about $1\mu\mathrm{m}$ which is about two orders of magnitude smaller than $\lambda_J$ of Josephson junctions. Then, using cuprate single crystals we easily imagine new devices which is analogous to Josephson gate as shown in Fig. 2 (A). The minimum size of the proposed single crystal devices are $\ell \simeq 2\mu m$ and $h \simeq 2\lambda_{ab}$. Then the minimum area is $h\ell \cong 0.2\mu\mathrm{m}^2$, which is smaller than fast and high density CMOS devices. It is possible to fabricate high density and fast switching integrated circuits with single crystal superconductors of which performances are superior than that of existing CMOS technology[12].

In order to develop the proposed single crystal devices, it needs to grow high quality single crystals with enough anisotropy and no defect. The peculiar performances of the proposed single crystal devices are as follows.

(1) Operating frequency of $\omega_p \simeq 5THz$.
(2) Switching time $\tau_s \simeq 1/\omega_p \simeq 0.1ps$.
(3) The minimum device size of $4\lambda_c\lambda_{ab} \simeq 0.2\mu m^2$.

The proposed single crystal devices work at about two orders of magnitude higher frequency range than both existing Josephson devices and fast CMOS devices and highly dense integrated circuits comparable to CMOS devices may be developed.
As the critical current density $j_0^s$ of cuprate single crystals are so high as $\cong 10^{11}\mathrm{A/m^2}$ (Table I), single crystal devices can be used as large current superconducting switches which are useful to control the current of high field superconductive magnets. For example, if the sizes of the device shown in Fig.2 (A) as $h = 1\mu\mathrm{m}$, $\ell = 2\mu\mathrm{m}$ and $w = 0.1\mu\mathrm{m}$ the maximum superconducting gate current $I_g = 50\mathrm{mA}$ at a zero voltage state switches to a voltage state of $V_0 = 100\mathrm{mV}$ by applying an input current of $I_c = 2\mathrm{mA}$.

Analogous to thyrist switches, parallel operations of such superconducting switches achieve a large current superconducting switch which is not yet existing. As the proposed devices consist of high quality single crystals with no imperfections, quite low noise performance is expected.

High quality $La_{2-x}Sr_xCuO_4$ single crystals were grown already[13]. Recently high quality $Bi_2Sr_2CaCu_2O_8$ single crystals are also grown and used for experiments of plasma resonancec[4]. $Bi_2Sr_2CaCu_2O_8$ single crystals may be good candidate materials for the proposed devices. In order to realize the proposed single crystal devices, important items to be investigated are flux quantum size interference effect and flux flow velocity along the ab plane in single crystals. The quantum-size interference effect is well know as Fraunhofer pattern in Josephson junctions. The magnetic field (H) dependence of the critical current $\Phi_c($ of junctions shows Fraunhofer pattern and is important to get current gain in a switching gate as shown in Fig.1 (B). The quantum-size effect of $Bi_2Sr_2CaCu_2O_8$ were measured recently using single crystal whiskers[14]. Frounhofer-like patterns are observed in $I_c$ -H curves of single crystal whisker junctions with several $10\mu m$ size (Fig.3). They observed clear periodic patterns when the size of $Bi_2Sr_2CaCu_2O_8$ whisker junctions are smaller than about $20\mu m$.

The flux flow velocity $v_F$ along ab-plane in cuprate single crystals is an important parameter to determine the switching time $\tau_s = \lambda_c / c_s$ where $c_s$ is the velocity of electromagnetic waves (Swihart velocity) and becomes the maximum flux flow velocity[15]. As the output voltage $V_0$ of the single crystal gate is expressed as

$V_0 = Bhv_F$ -------(4)

fast velocity $v_F$ is important to get high value of output $V_0$ to drive quickly next gates[11]. Using $Bi_2Sr_2CaCu_2O_8$ single crystals, the values of $v_F$ were already measured[16],[17] and estimated as $v_F \simeq 3\times10^5 m/s$ , which is fast enough to obtain high output voltage of the proposed devices. Recent investigations on flux flow of $Bi_2Sr_2CaCu_2O_8$ single crystals revealed quite new phenomena. Hechtfischer et. al[18] measured the flux flow velocity $v_F$ in $Bi_2Sr_2CaCu_2O_8$ single crystals in applied parallel field to ab plane and found that $v_F$ increases beyond the lowest mode verocity (Swihart velocity). They explain the increased velocity and observed wide band GHz radiation by Cherenkov radiation from stacked Josephson junctions in a single crystal.

## 3) Summary

The crystal structures of cuprate superconductors consist of stacked double layers and each layer is electrically conductive and non conductive. Between two conductive layers separated by non conductive one, superconducting tunneling effect are observed which is called as intrinsic Josephson effect of a single crystal of a cuprate superconductor. In this paper, we proposed the new fast and small switching gate based on intrinsic Josephson effect of singe crystals of a cuprate superconductors. The performances of the proposed gates are about two orders of magnitudes superior than those of existing Nb Josephson devices. Its switching time is about sub. picosecond and operating frequency is up to several THz region. It is expected to develop higher speed and more dense integrated circuit technology than those of existing semiconducting and Josephson devices. Some of recent progress relating to the new devices are reviewed.

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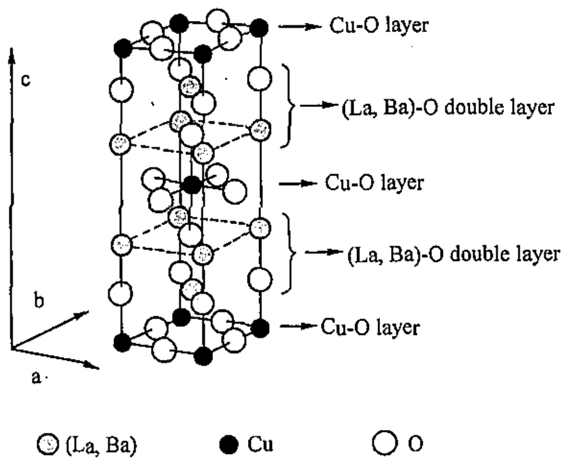

a) The crystal structure of a high $T_c$ cuprate $La_{2-x}B_{ax}CuO_4$ with stacked layers of $Cu-O$ and $(La,Ba)-O$.

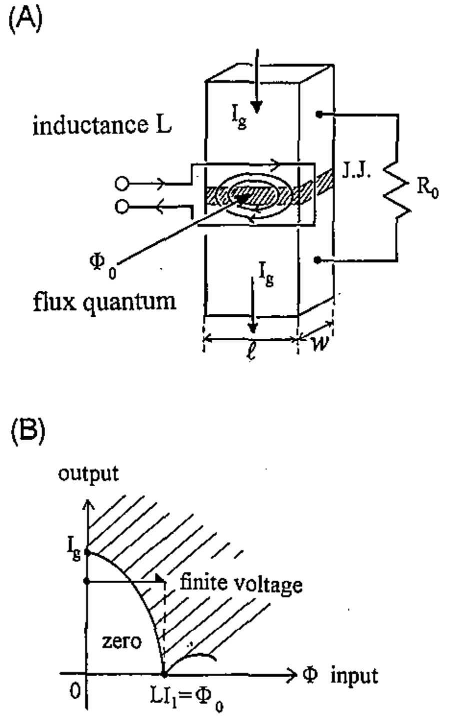

Fig.1

The model of Josephson junction switch.

The device structure (A) and input-output characteristics(B).

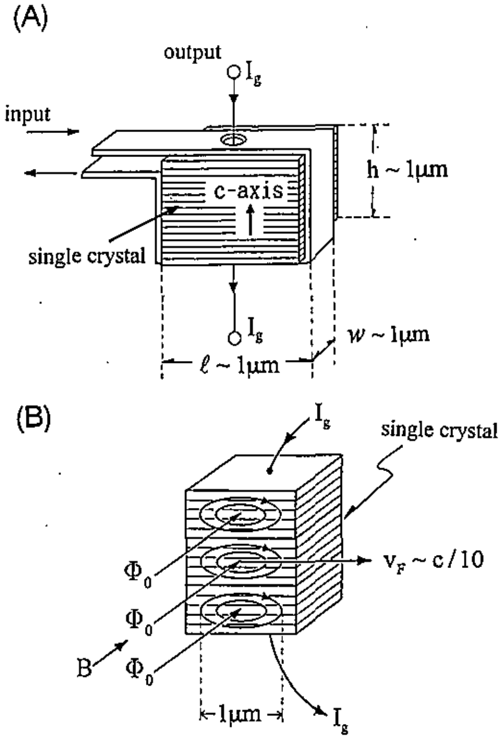

Fig.2

The model of switching gate made by a single crystal of a high Tc cuprate superconductor. The device structure (A) and induced flux quantum chain (B) in the single crystal by application of an input flux of $B^s_{c1}h\ell$.

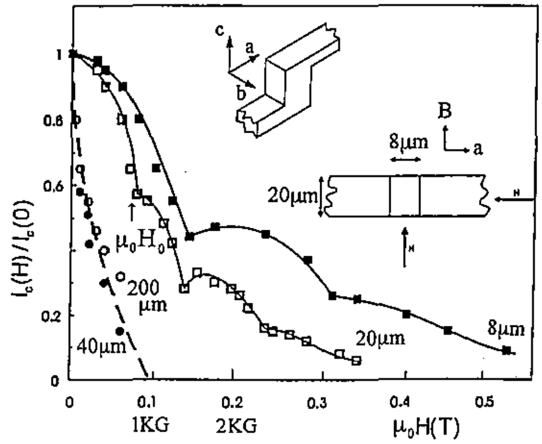

Fig.3

Normalized dependencies of critical currents of $Bi_2Sr_2CaCu_2O_8$ junctions across the layers $I_c(H)/I_c(0)$ at $T = 4.2K$ on magnetic field H parallel to the layers for samples of different sizes L:■, 8 μm;□, 20 μm; ● , 40 μm; and ○, 200 μm . The inset shows the geometry of the junctions for which H has been rotated and applied ‖ a and ‖ b, respectively[14].