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Terahertz responses of high-T_c ramp-type junctions on MgO

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Abstract. We successfully fabricated the high-T_c ramp-type junctions with $PrBa_2Cu_{3-x}Ga_xO_{7-\delta}$ (PBCGO:x=0.1, 0.4) barriers on MgO substrates. The junctions showed RSJ-like I-V curves with increased thermally and voltage activated conductivity. The I_cR_n products for these junctions scale very well with the Ga-doping. Using far infrared laser radiations, we confirmed terahertz (THz) responses of these junctions. The junction with PBCGO (x=0.4) had I_cR_n products of ~1mV at 4.2K and showed Shapiro steps with THz-wave irradiation, without any additional antenna structure.

1. Introduction

Superconducting electronics based on high-T_c Josephson junctions (HTJJs) have several advantages and a number of applications has already been demonstrated. One of the most promising application lies in high frequency applications. The substrate choice for terahertz (THz) applications is very important because of their frequency dependent dielectric behaviour. Among the oxide substrates, MgO, Al_2O_3 and $BaZrO_3$ have low dielectric constants and low loss tanδ and show low reflectance up to several THz. From literature[1] and our investigations, we conclude that these substrates are the most suitable ones for THz applications.

For practical THz applications, there are additional demands for the fabrication of Josephson junctions: in general, HTJJs need to match to waveguide or quasi-optical input circuits with impedances of the order of 50Ω. Furthermore, for high temperature operation, the critical current of the junction has to exceed a certain value to overcome thermal noise rounding. Therefore, Josephson junctions with high I_cR_n products are needed. Ramp-type Josephson junctions are, until now, the only candidate if one requires tunable junction parameters, as mentioned before. $PrBa_2Cu_{3-x}Ga_xO_{7-\delta}$ (PBCGO) as barrier material leads to high I_cR_n products and reproducibility of the I_cR_n products. So far, I_cR_n products of 8mV are obtained, using a 40% Ga-doped PBCO barrier[2].

In this study, we demonstrate that it is possible to make ramp-type junctions on MgO substrates using Ga-doped PBCO barrier. Moreover, we confirmed that ramp-type junction can respond to THz irradiation from a far infrared (FIR) laser.

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2. Experimantal

High-T_c ramp-type junctions were fabricated on MgO(100) substrates. The fabrication process of our junctions was described previously[3]. Starting from a sputtered $DyBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$(DBCO/PBCO) bilayer, a ramp with an angle of ~20° with respect to the substrate surface was etched using an Ar-ion beam. The ramp surface was subsequently ion-beam cleaned at low energy to remove damage from the interface. Next, the ramp was covered by a PBCGO barrier layer and a DBCO counterelectrode. Final junction definition, wiring, and metallization were performed by a conventional photolithographic process. Barrier thickness d for the most junctions reported here is about 10nm, as inferred from the calibrated growth rate.

I-V curves were measured by conventional four-probe method. dV/dI curves were observed using standard low-frequency ac lock-in techniques. Microwave (8~20GHz) and millimeter wave (100GHz) were generated by a synthesized signal generator and a Gunn diode, and were fed to ramp-type junctions using coaxial cable and waveguide, respectively. THz wave signals were generated by a far-infrared (FIR) laser, pumped by a 38W CO_2 laser, yielded ~40mW on the 761.7GHz formic acid line and ~100mW on the 1.397, 1.627THz diflorometan line and ~120mW on the 2.524THz methanol line. THz wave signals were fed to the junctions mounted on cold stage in an infrared cryostat via quasi-optical system consisting of a TPX lens and a hyperhemical lens made of high resistivity Si.

3. Results and Discussion

Figure 1 shows typical temperature dependence of I-V characteristics (IVCs) for a ramp-type junction on a MgO substrate. They can be very well described by the resistively shunted Josephson junction (RSJ) model. The normal resistance of the junction is decreasing with increasing temperature. If the junction electrical properties are determined by grain-boundary junction, R_n value is independent on temperature. This indicates that the IVCs of the junctions are dominantly determined by the PBCGO barriers.

Electric transport properties of the ramp-type junctions with PBCGO are well described by direct tunneling and resonant tunneling via n localized states (L.S.)[4] Using expressions derived by Glazman and Matveev[5], two important limits of activation for the resonant tunneling component $G_n(T,V)$ can be distinguished:

$$G_n(T,V) \propto T^{n-2/(n+1)} \quad (eV \ll k_BT)$$
$$G_n(T,V) \propto V^{n-2/(n+1)} \quad (eV \gg k_BT).$$

The dependence of the activated conductivity on temperature and bias voltage for the junctions with PBCGO barrier on MgO show $G_{total} - G_{lin} \propto T^{4/3}$ and $V^{4/3}$, consistent with

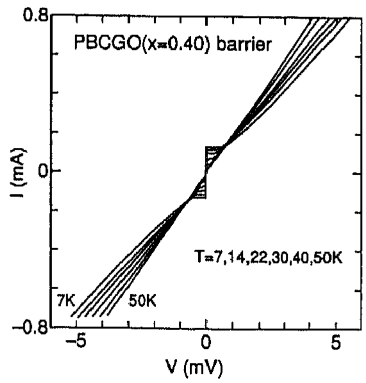

Fig. 1. Typical temperature dependence of IVCs for a ramp-type junction with PBCGO (x=0.4) barrier of 10nm on a MgO substrate.

those obtained from the junctions on $SrTiO_3$. The exponent of 4/3 is corresponding to indirect passage vià 2 L.S.

It has been reported that values of I_cR_n product depend on Ga-doping level and those values are about 1mV for x=0.1 and several mV for x=0.4, concerning to the ramp-type junctions on $SrTiO_3$ with the barrier thickness of ~10nm. For the ramp-type junctions on MgO, I_cR_n values were also dependent on Ga-doping level. However, values of I_cR_n product were several times smaller than those for the ramp-type junctions on $SrTiO_3$. One possible reason for this is that Ga atoms doped in PBCO don't work effectively to eliminate localized states because of low deposition temperature for PBCGO barrier, compared to that on $SrTiO_3$ substrates.

For high frequency application, it is better to minimize capacitive shunt component. In the case of using $SrTiO_3$ substrates, typical capacitance per μm^2 is ~50fF/μm^2. In the case of the junctions on MgO, non-hysteretic IVCs were observed even at low temperature. Even if the junctions on MgO have capacitive shunts, they are two order of magnitude smaller than those for the junctions on $SrTiO_3$.

Figure 2 shows I-V curves of a junction with PBCGO (x=0.1) barrier under irradiation of 100GHz millimeter wave and taken at different powers. Power dependence of the step height can be fitted well with the nth Bessel function $J_n(I_{rf}/I_c)$. Under the maximum irradiation power, Shapiro steps can be observed up to 12mV without any antenna structure, as shown in Fig. 3. This maximum response voltage might be increased by using an antenna structure because maximum response voltage was observed up to 17mV on a grain boundary junction with a log-periodic antenna on a MgO bicrystal substrate. These results suggest that HTJJs may respond up to 5~10 THz wave region.

Using the FIR laser, it was confirmed that the ramp-type junctions on MgO can respond to millimeter wave (761.7GHz) and THz wave (1.397THz and 1.627THz). Figure 4 shows dV/dI curve of a junction with PBCGO (x=0.4) barrier under irradiation of 1.627THz wave from the FIR laser. Clearly distinct minima were observed at the expected voltages of $\pm\Phi_0 f_r \sim \pm$3.4mV. Very small Shapiro steps were also visible on I-V curves. Compared to the theoretical induced step height, detected power is estimated to

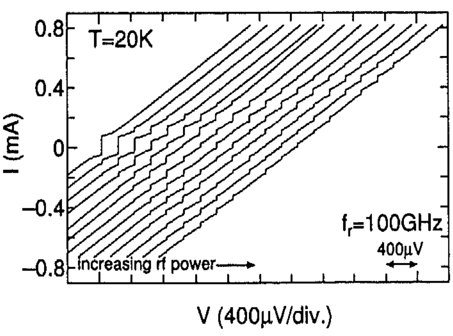

Fig. 2. I-V curves of a junction with PBCGO (x=0.1) barrier under irradiation of 100GHz millimeter wave and taken at different powers.

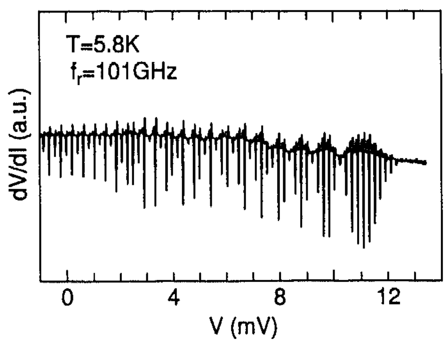

Fig. 3. dV/dI curves of a junction with PBCGO (x=0.4) barrier under irradiation of 100GHz millimeter wave with the maximum power.

be order of 10^{-7}W at the maximum and this value is 6 orders of magnitude smaller than the input power. Under irradiation of 2.524THz wave with the input maximum power of 150mW, no response was observed. In this THz region, transmittance of MgO substrate is rapidly decreased because of its dielectric behavior. Since optical properties of substrates restrict the performance of THz detectors and generators in this THz region, it is very important which kind of material is used for the substrate.

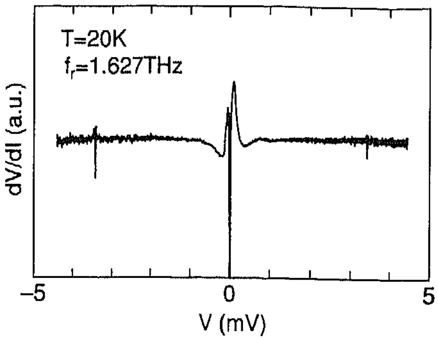

Fig. 4. dV/dI curve of a junction with PBCGO (x=0.4) barrier under irradiation of 1.627THz wave from the FIR laser.

4. Conclusions

We have successfully fabricated the high-T_c ramp-type junctions with PBCGO (x=0.1, 0.4) barriers on MgO substrates. The junctions showed RSJ-like I-V curves with increased thermally and voltage activated conductivity. The I_cR_n products for these junctions scale very well with the Ga-doping. This indicates that the I-V characteristics of the junctions are dominantly determined by the PBCGO barriers, instead of additionally introduced grain boundaries in the vicinity of milled ramp surface. Using far infrared laser radiations, we confirmed terahertz responses of these junctions. The junction with PBCGO (x=0.4) had I_cR_n products of ~1mV at 4.2K and showed Shapiro steps with THz-wave irradiation, without any additional antenna structure. These results are promising THz applications using the ramp-type junctions with PBCGO barriers fabricated on MgO substrates.

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