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Preparation and Characteristics of a Superconducting Base Transistor with an $Au/Ba_{1-x}K_xBiO_3$/Niobium-Doped $SrTiO_3$ Structure

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We observed fundamental operation of a superconducting-base transistor using a $Ba_{1-X}K_XBiO_3$(BKBO) high-Tc superconductor. The transistor was composed of a planar-type Au/natural-barrier/BKBO/niobium doped $SrTiO_3$ (STO:Nb). Au, BKBO and STO;Nb correspond to the emitter, base and collector in this transistor, respectively. An increment in the collector current was observed as the emitter current increased at 4.5 K. The transistor with a 100 nm thick showed a maximum common-base current gain of over 0.5.

1. INTRODUCTION

The high technological potential of high-Tc superconductors has given rise to a considerable amount of research aimed at fabricating electronic switching devices using these materials. In recent years, superconductor-based transistor-like devices have been researched because they are believed to be capable of very high frequency work, low-temperature operation, lower power consumption than conventional solid-state devices, and simplification of low-temperature electrical circuit designs. The low-energy injection type superconducting-base transistor proposed by Frank et al. is one example of these promising three-terminal devices[1]. It is thought to be particularly suitable for practical use in low temperature analogue and microwave devices. This transistor has a junction structure composed of a superconductor (S), a normal-metal (N), an insulator (I), and a semiconductor (SE), arranged as an N/I/S (or S/I/S) tunneling emitter-base junction and S/SE base-collector heterojunction, as shown in Fig. 1. However, a number of problems have become apparent during device fabrication with high-Tc copper based superconductors such as YBCO and BSCCO [2,3]. These problems are mainly due to a very short coherence length, strong anisotropy and absence of BCS gap-like features.

However, $Ba_{1-X}K_XBiO_3$ (BKBO) with a cubic perovskite structure is the highest-Tc (30 K) oxide superconductor not containing Cu ions [4-6], and it is thought to have three advantages over high-Tc copper oxides in device applications: a cubic isotropic structure, several times longer coherence length estimated to be 50-70 Å [6,7] and electron-type carriers [8,9]. In this paper, we report on fundamental electric properties of a superconducting-base transistor with an Au/natural-barrier/BKBO/niobium-doped $SrTiO_3$ (STO:Nb) structure.

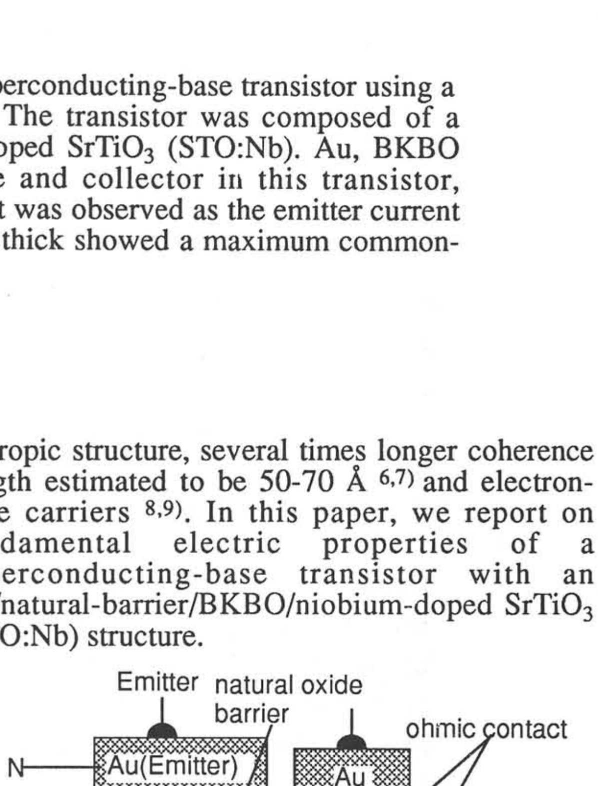

Fig. 1 Cross sectional diagram of superconducting-base transistor with an Au/BKBO/STO:Nb structure. Emitter is made of Au, base is BKBO, and collector is STO:Nb. N, I, S and SE are normal metal, insulator, superconductor and semiconductor, respectively.

2. EXPERIMENTAL PROCEDURE

The fabrication of an Au/natural-barrier/BKBO/STO:Nb superconducting-base transistor is shown in Fig. 2. First, STO:Nb(110) with a 0.1 wt% niobium concentration was prepared as a collector layer (Fig. 2(a)). This wafer (collector) is known as an n-type semiconductor [10] and had a carrier density of $2x10^{19}$ cm^{-3}. Then, BKBO thin film (superconducting-base) a 100 nm was prepared on STO:Nb by rf-sputtering (Fig. 2

(b)). Electrical properties of S/SE base-collector heterojunction with a BKBO/STO:Nb depends much on the sputtering conditions during fabrication. We optimized the conditions in order to fabricate junctions with less interfacial layer and less interfacial resistance. Details of the fabrication

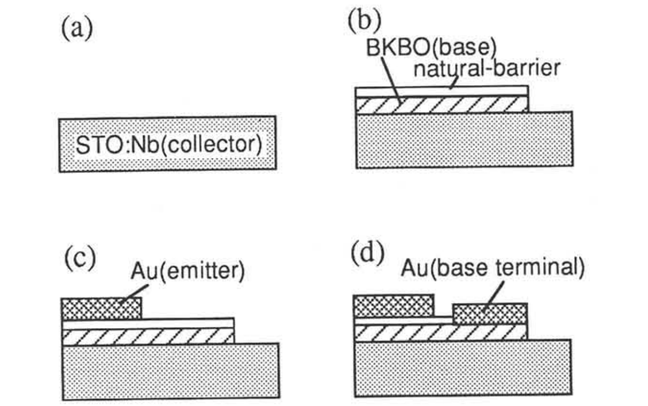

Fig. 2 Fabrication of an Au/natural-barrier/BKBO /STO:Nb transistor: (a) n-type semiconductor substrate STO:Nb preparation. (b) Epitaxial deposition of BKBO thin film using RF-sputtering. (c) Au deposition as an emitter. (d) Au deposition as an ohmic-base contact after annealing at 200°C in a vacuum chamber.

procedure have been described previously [11,12]. Au was evaporated onto BKBO to fabricate emitter. (Fig. 2(c)). A surface natural insulator barrier (tunneling barrier) with a contact resistance in the order of 10^{-2} Ω/cm^2 was always created on BKBO after Au deposition at room temperature. The junction resistance of Au/natural-barrier/BKBO could be controlled a range of over several orders by controlling the substrate temperature at Au evaporation. Au was evaporated and vacuum annealing at 200°C was carried out for base contact formation. (Fig. 2(d)).

The I-V characteristics of each junction were measured using the conventional four terminal method. Common-base three terminal current transfer ratios were measured to determine the transistor characteristics.

3. RESULTS AND DISCUSSION

(i) Au/natural-barrier/BKBO junction

Figure 3 shows I-V characteristics of an Au/natural-barrier/BKBO emitter-base junction measured at 4.5 K. The normal junction resistance was about 10 Ω. Non-linearity due to the BKBO gap structure is observed. The tunneling factor G_{N0}/G_{S0} of this device at 4.5 K was about 20, (G_{N0} and G_{S0} are the differential conductances at 0 bias under normal and superconducting states, respectively). The natural-barrier on the BKBO surface is of sufficient quality for use as an insulator layer for the tunneling junction. A reproducible ohmic-base contact with a resistance of less than 10^{-6} Ω/cm^2 could be obtained by Au evaportion and vacuum annealing at 200°C.

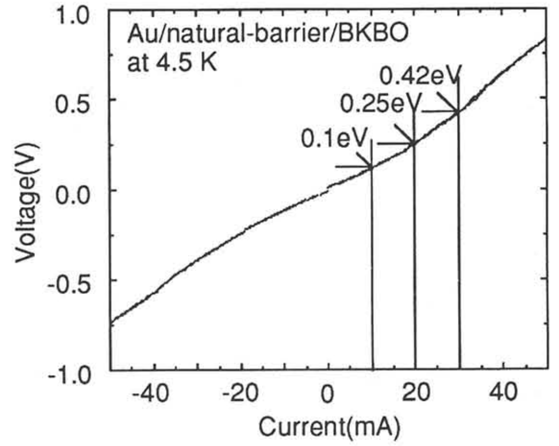

Fig. 3 I-V characteristics of an Au/natural-barrier/BKBO junction measured at 4.5 K for an emitter/bas tunneling junction. The inset shows a reduced I-V curve for the same junction.

(ii) BKBO/STO:Nb junction

I-V characteristics of BKBO/STO:Nb junction has asymmetric structure like as Schottky junction reflecting the asymmetry of this heterojunction. One example of this junction is shown in the case of $I_E = 0$ mA in Fig. 4, which shows the I_C - V_{BC} characteristics as a function of I_E, where I_E, I_C and V_{BC} are emitter current, collector current and base-collector bias, respectively. Right side of horizontal-axis shows reverse bias of BKBO/STO: Nb junction. The breakdown voltage of this junction has very small value of less than 1 V, because electron carrier density of STO:Nb is value of 2×10^{19}/cm^3, which is much larger than conventional semiconductor and so that the barrier width of the junction is much thinner than conventional Schottky junction and the breakdown voltage becomes much smaller than those of conventional Shottky junctions [12].

(iii) Transistor measurements

I_E is injected into the base layer when a higher emitter-base bias (V_{EB}) than the superconducting-gap energy of BKBO (4 mV) is applied. Carrier transport into the collector can be observed using common-base I-V measurement. I_C was found to rise as I_E increased in Fig. 4. When I_E was 10 mA, the increment in I_C was much less than 10 mA at each V_{BC} point. However, when I_E was 20 mA, a large enhancement in I_C was observed around V_{BC} = 0 V. From Fig. 3, if we assume that V_{EB} is 0.1 V when I_E is equal to 10 mA, then the maximum quasi-particle energy injected into the base layer is less than 0.1 eV, and most of these injected carriers cannot overcome the base-collector junction barrier. But when I_E is 20 mA and V_{EB} is 0.25 V,

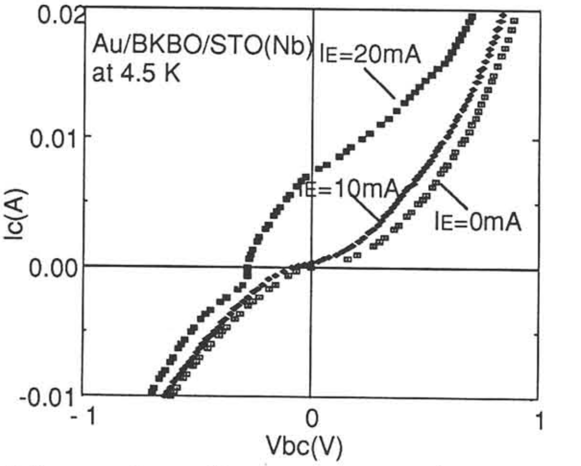

Fig. 4 Common-base collector current v.s emitter current characteristics measured at 4.5 K when I_E = 0 mA, I_E = 10 mA and I_E = 20 mA.

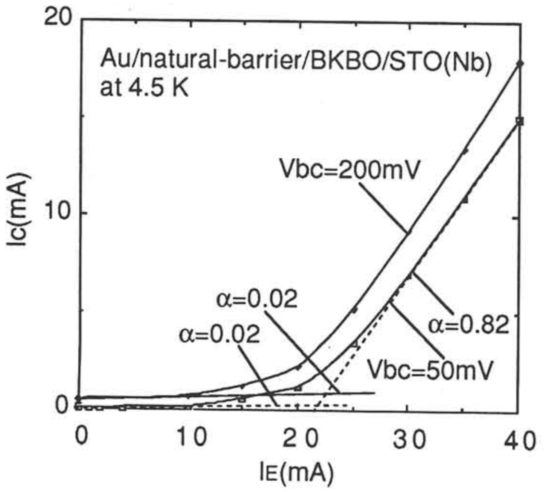

Fig. 5 Emitter current dependence of common-base collector current measured at 4.5 K for various base-collector bias, Vbc = 50mV and 200 mV.

some quasi-particles are able to overcome the collector barrier. When I_E is less than 20 mA, the current transfer ratio, α, (dI_C/dI_E) of low-energy electrons was found to range from 0.01 to 0.1. A drastic rise in α to over 0.5 was observed at I_E values above 20 mA. The transfer efficiency turning point in Fig. 5 corresponds to the V_{EB} value of 0.25 V in Fig. 3. This is because quasi-particles whose energy is higher than the 0.25 eV of the base-collector barrier height are able to cross the 100 nm BKBO base layer ballistically, with almost no reflection at the base-collector hetero-junction, as in the case of BEEM [13].

Previousely, it was very difficult to fabricate a three terminal device using a metal (or superconductor)-semiconductor structure for the base-collector with high transfer ratio [14,15]. This was thought to be due to the existence of a surface degradation layer or surface states on either material. Moreover, the oxide superconductor-semiconductor junction had to be constructed epitaxially because oxide superconductors can only assume a superconducting state when it has a crystalline structure. However, we are now able to satisfy epitaxial growth of an oxide superconductor on an oxide semiconductor.

Furthermore, since the α exceeds 0.5 in the case of the BKBO/STO:Nb junction, it seems there is less interfacial damage layer or surface state formation in the oxide superconductor-oxide semiconductor heterojunction.

4. CONCLUSION

Our study has led to the following conclusion:
i) Simple annealing treament in a vacuum chamber has enabled to control the junction resistance of Au/natural barrier/BKBO junction.
ii)A BKBO/$SrTiO_3$:Nb (an oxide superconductor-oxide semiconductor) base-collector junction can transport hot electrons with high transfer efficiency (transport ratio, α, exceeds 0.5 for energy higher than 0.3 eV) just like normal metal/semiconductor in a hot electron transistor.
iii) A transistor using an oxide superconductor is feasible.

ACKNOWLEDGMENT

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