Grain boundary weak link in *a-b* plane in MgB_2 film

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The authors have fabricated the MgB_2 bridges 850–6000 nm in width on bicrystal (111) MgO substrates with in-plane grain boundaries of the two types: 13°/13° ⟨110⟩ and 13°/13° ⟨112⟩. Annealing in oxygen of the films on ⟨110⟩ bicrystal substrates leads to a systematic decrease of critical current, a widening of the transition temperature width, and an improvement of the shape of *IV* curve that finally looks more like a Josephson junction. They have measured a response of such samples to the microwave radiation at 110 GHz with the voltage amplitude up to 0.5 mV. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2396917]

We suppose that a (111) magnesium oxide substrate is suitable for a (001) MgB_2 film growth due to their close lattice constants in the planes, that is, $a=0.298$ nm in ⟨110⟩ for the former and $a=0.308$ nm in ⟨110⟩ for the latter. In order to obtain a weak link we grow a MgB_2 film on a bicrystal substrate. This provides an inheritance of the artificial grain boundary from the substrate into the film. We would expect a formation of an oxide barrier between two superconducting parts due to more active oxygen diffusion in the region of boundary. The B_2O_3 boundaries of 1–3 nm thickness between MgB_2 grains were observed by scanning transmission electron microscopy in Ref. 1. It could also be a metallic MgB_4 (Ref. 2) or amorphous MgB_2 boundary of 5–20 nm thickness separating MgB_2 crystalline grains as was reported in Ref. 3. These types of boundaries can give rise to superconductor-normal metal-superconductor (SNS) or superconductor-insulator-superconductor (SIS) types of Josephson junctions.

Bicrystal (111) MgO substrates were produced by a solid phase intergrowing method.[4] For that the two pieces of MgO single crystals were put together in a symmetric crystallographic position, contacting by flat surfaces oriented parallel to [(110)−13°)] and [(110)+13°] correspondently for the one bicrystal type and parallel to [(112)−13°] and [(112)+13°] for the other. The pieces were rotated in the surface of contact in such a way that their (111) planes were parallel to each other. In such position the systems were welded. The produced bicrystals were cut parallel to common (111) plane and polished for fabricating bicrystal substrates. Thus, we fabricated the two types of bicrystal substrates oriented as (111) with artificial grain boundary perpendicular to the surface and with symmetric rotation of crystal lattice by $2\times13°$. In the first bicrystal the boundary makes angles 13° to the axes ⟨112⟩, and in the second one to the axes ⟨110⟩. For comparison the (111) single crystal substrates were also fabricated.

MgB_2 films were grown by coevaporation in a custom-designed ultrahigh-vacuum chamber (the base pressure $\sim5\times10^{-10}$ Torr) from pure Mg and B sources using multiple electron guns.[5] The growth temperature was 280 °C and the

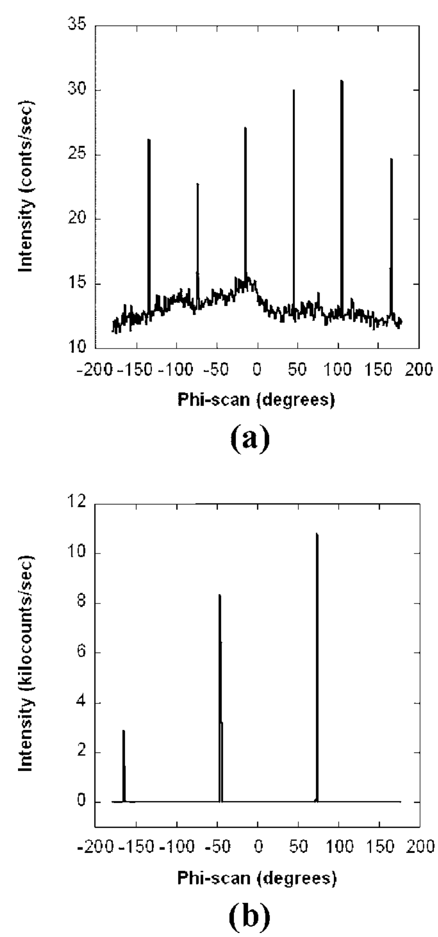

FIG. 1. X-ray diffraction phi scan of (001)MgB_2 film from planes of (101) type in top panel (a) and (111) MgO substrate from planes of (311) type in bottom panel (b).

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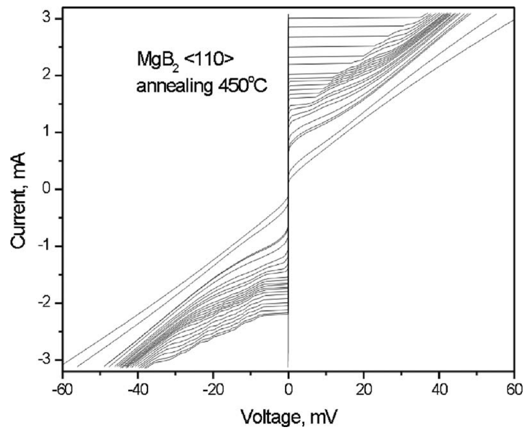

FIG. 2. *IV* curves for annealed at 450 °C bicrystal bridge 0.9 μm wide measured at temperatures from 25.2 to 29.8 K.

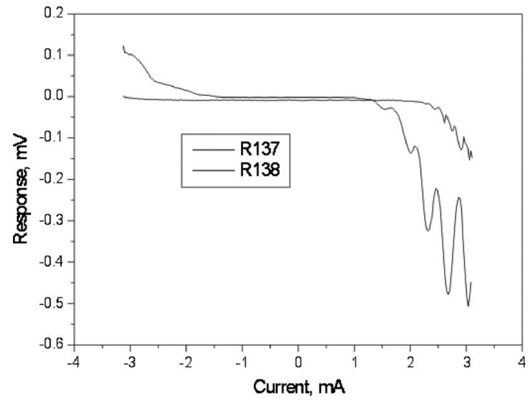

FIG. 3. Voltage response at 110 GHz in dependence on bias current.

growth rate was 3.8 Å/s. The evaporation rate of Mg to that of B was set three times as high as the nominal rate so as to compensate the loss of Mg due to reevaporation.

Heterostructures consisting of (111) MgO substrate and (001) MgB_2 film were studied with a four-circle x-ray diffractometer X-Pert Philips in a phi-scan mode. As an x-ray reflection plane for (111) MgO substrate we chose (311) plane types. For a film analysis the (112) reflection planes were used. One can see that the reflection angles from the film (112) planes [Fig. 1(a)] are shifted by 60° compared to the reflections from (311) planes of substrate [Fig. 1(b)]. This means that our (001) MgB_2 films are epitaxial, single domain, and their crystal lattice is linked to a (111) MgO substrate lattice.

The MgB_2 films were patterned in a form of microbridges 0.9 μm in width and 6 μm in length and integrated with log-periodic planar antennas. The *IV* curves measured immediately after the fabrication show critical currents of several milliamperes and a normal resistance of 20–60 Ω. The annealing in the oxygen of films on bicrystal substrates leads to a systematic decrease of critical current, a widening of the transition temperature width from 2 to 5 K, and an improvement of the curve shape that finally looks more like a Josephson junction (see Fig. 2). In a single-crystal case *IV* curves did not show significant changes. For the second bicrystal sample ⟨112⟩ the annealing at 600 °C completely suppressed critical current and increased resistance over 1 kΩ for widest junction and to infinity to the rest ones. We can also mention a specific ripple structure in *IV* curves at the temperatures close to the critical one. It is similar to regular step structures due to successive establishment of phase slip centers that were observed in long superconducting thin film microbridges.[6]

We have also measured a voltage response for such bicrystal MgB_2 samples to the microwave radiation at 110 GHz (see Fig. 3). Response maxima, in general, follow to the dependencies of dynamic resistance around phase slip features.

For lower temperatures down to 4 K the *IV* curves are hysteretic and further improvement can be achieved by optimizing misorientation angle, annealing time, and annealing temperature. For comparison with other MgB_2 weak links we can refer to Ref. 7 where Josephson junctions were fabricated using focused ion beam milling. For a junction with small value of the critical current (I_c=3 μA at 4.2 K), they observed Shapiro steps when the junction is irradiated with microwave power at 9 GHz. Response in this case does not exceed few microvolts.

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