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Magnesium diboride superconductor thin film tunnel junctions for superconductive electronics

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Based on superconducting MgB_2 films with higher critical temperature of 39 K and the advantage of the conventional superconductors, those that follow Bardeen-Cooper-Shrieffer theory, fabrication of quasiparticle, and Josephson tunnel junctions have been investigated. To explore the potential of MgB_2 for superconductive electronics, the essentials such as clean high quality thin film surfaces and reproducible tunnel junction fabrication are addressed. Our results show clean tunneling characteristics for *in situ* prepared MgB_2 junctions on Si wafer with the measured superconducting energy gap values in good agreement with theory and the feasibility of the technology. The recent results on all-epitaxial $MgB_2/MgO/MgB_2$ Josephson junctions will be also reported. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2390622]

INTRODUCTION

After the discovery of superconductivity in the intermetallic compound magnesium diboride (MgB_2) with a high critical temperature of 39 K,[1] a number of groups have investigated MgB_2 due to its great potential for superconductive magnets and electronic applications. In comparison with the conventional metallic superconductors, MgB_2 has the potential for higher operating speed due to its larger energy gap. For the realization of superconducting electronics (SCE) the availability of high quality thin films and the technology to fabricate Josephson circuits based on these films are essential.[2,3]

The growth of MgB_2 thin films, however, was challenging and a number of problems had to be solved, especially in order to obtain smooth and single-phase films suitable for multilayer structures that are important for the application in superconducting electronics. The problems such as high volatility of magnesium, oxygen impurities, and surface roughness had to be overcome.[4] Due to the high vapor pressure of Mg, the phase stability of MgB_2 with high crystallinity is the most serious problem. Therefore, earlier two-step growth, in other words, *ex situ* postannealing was developed. Later, one-step growth, namely, *in situ* physical vapor deposition, such as molecular beam epitaxy (MBE) was reported.[2,4] The detailed procedure for the growth of single-phase epitaxial MgB_2 films on Si(111) substrate has been described in our earlier papers.[4,5]

The electronic structure and superconducting (SC) behavior of MgB_2 are theoretically well described using the conventional electron-phonon mechanism.[6,7] Anisotropic SC energy gaps, Δ_σ for the two quasi-two-dimensional σ bands and Δ_π for the pair of three-dimensional π bands, ascribed to two different parts of the Fermi surface, were predicted theoretically.[8] The calculation by Choi *et al.*[9] showed that the electronic states are dominated by orbitals in the boron plane coupling strongly to specific phonon modes giving rise to multiple gaps. Those authors predicted SC energy gaps from 6.4 to 7.2 meV on the σ band and from 1.2 to 3.7 meV on the π band. Although the multiband picture of superconductivity in MgB_2 has been studied to determine the SC energy gaps by various surface sensitive techniques such as probe tunneling, point contact Andreev reflection, high resolution angle resolved photoelectron spectroscopy, etc.,[10–16] leakage free planar tunneling junctions have provided the most reliable SC gap information in conventional superconductors.[5,17] Indeed, not only for fundamental studies but also for many superconductor electronic applications of MgB_2-based junctions, it is important to know how the two-band superconductivity will play a role. Besides, the pertinence of MgB_2 for SCE strongly depends on the possibility of making well-controlled Josephson junctions. In this paper our recent results on the SC characteristics of epitaxial MgB_2 films using MgB_2-based tunnel junctions and the fabrication of Josephson junction, in particular, all-MgB_2 junctions (such as $MgB_2/MgO/MgB_2$) are reported.

SAMPLE PREPARATION

MgB_2 thin film planar junctions were prepared, all *in situ*, using shadow masks in a MBE system with the base pressure in the 10^{-10} Torr range. Onto an etched Si(111) substrate, 50 Å of MgO was grown by e-beam evaporation at a substrate temperature (T_S) of 563 K. This was followed by the coevaporation of Mg (from a Knudsen cell) and B (from an e-beam source) with independent rate controllers to obtain MgB_2 films with thickness of 560 Å. The optimum conditions required to obtain high quality MgB_2 films[4] and to fabricate MgB_2-based tunnel junctions with Al_2O_3 tunnel barriers ($MgB_2/Al_2O_3/V$) (Ref. 5) are described in our earlier studies. $MgB_2/MgO/MgB_2$ junctions were fabricated

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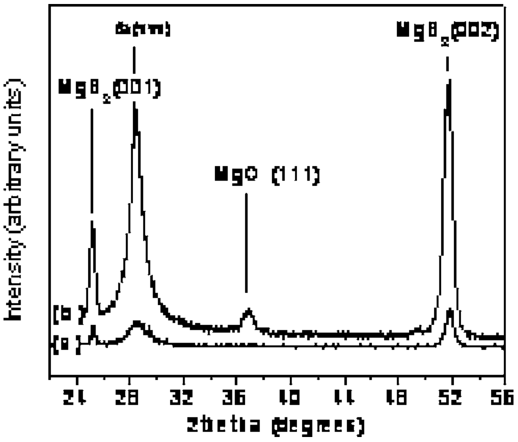

FIG. 1. XRD θ-2θ patterns of MgB_2 thin film grown at 563 K (a), and of MgB_2/MgO/MgB_2 trilayer with 100 Å thick MgO film (b). 50 Å of MgO was deposited beyond these films as a capping layer to avoid the oxygen contamination.

slightly differently; MgO sandwiched between the two MgB_2 layers is the tunnel barrier. To cover the edges of the bottom MgB_2 film strips, a 70-Å-thick MgO film was deposited, thus defining the tunneling width (80 μm) of the bottom electrode. Cross strips of 560-Å-thick MgB_2 were again deposited as the top electrode, keeping the T_S of 563 K throughout. These junctions were protected with 50 Å of MgO film. The thickness of the barrier was varied to obtain tunnel junctions with an optimum resistance (R_j) in the range of a few ohms to a few kilohms.

RESULTS

The structural characterization of our MgB_2 films by x-ray diffraction show epitaxial growth, see Fig. 1(a). Spectrum (b) in Fig. 1 shows that we succeeded in obtaining as-grown high-quality MgB_2/MgO/MgB_2 epitaxial superconducting trilayer structure at our growth conditions over Si(111) with a 50 Å thick MgO seed layer. It is notable that the top MgB_2 film could be grown epitaxially on a MgO(111) barrier layer grown over a MgB_2 bottom film. One can see clearly that the peak intensity of MgO(111) becomes stronger as the thickness of MgO increases from 50 to 100 Å. It may be noted that the top MgB_2 film can grow with good epitaxy directly onto the MgO(111) layer because the lattice mismatch is only a ~2% for two unit cells of MgB_2 on a MgO(111) unit cell. Critical temperatures (T_c) of 28 and 33 K were obtained for the top and the bottom MgB_2 films, respectively. The lower T_c of the top MgB_2 film may be attributed to the poor microstructure at the MgO(111)/MgB_2 interface. The T_C needs to be further optimized.

The tunneling conductance for a MgB_2/Al_2O_3/V junction taken at 0.45 K is shown in Fig. 2. The zero conductance region is very well established up to nearly ±2.5 mV, and the main peaks are noticeably sharper, as expected for a good quality superconductor/insulator/superconductor (SIS) tunnel junction. The SC gaps (2Δ) of both the MgB_2 and the V films are determined unambiguously from the sum of conductance peaks. From the simple analysis, the Δ value for V is 0.70 meV, whereas for MgB_2, the Δ value is 2.4 meV, which we attribute to the π band (Δ_π).[8,9] Careful observation of this plot reveals additional features at voltages slightly higher than the main peaks as well as tiny voltage steps on either side of V=0. In the bottom part of this figure [see Fig. 2(b)], at higher voltages the conductance is amplified ten times in order to show the less well resolved second peaks (rather small in amplitude compared to the main peaks). The position of the second set of peaks is determined to be ±7.5 meV by taking the derivative of this curve, from which we obtain the σ gap of MgB_2, as Δ_σ=6.8 meV, which is due to the σ band (after subtracting the V SC gap). The tiny voltage steps (at ±0.6 mV) are attributed to the presence of a small amount of Josephson pair current in the junction. When we make the barrier thinner, we clearly see a large Josephson pair current, as shown in Fig. 3 for one such device. A current hysteresis, as well as self-induced voltage steps, was also observed in such structures with thinner barriers.

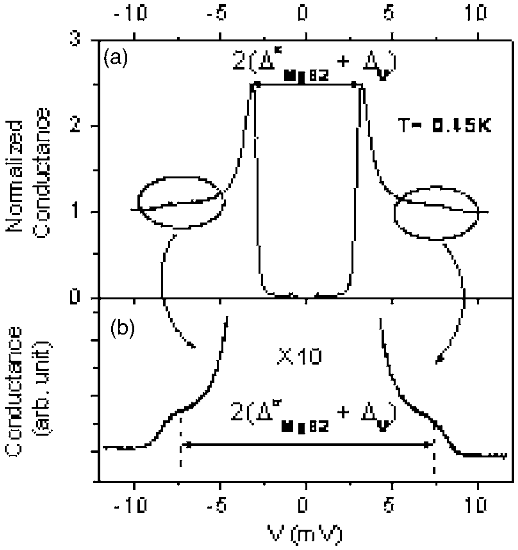

FIG. 2. Tunneling characteristics at lower temperature (0.45 K) showing not only the SC gap energy sum peaks due to π bands in MgB_2 and V but also those due to the σ band of MgB_2 and V.

We have also seen Josephson pair tunneling with MgO barriers, similar to that seen with Al_2O_3 barriers. MgO barriers were deposited from an e-gun source with a T_S at 563 K. The inset of Fig. 4 shows that we successfully grew all-epitaxial MgB_2/MgO/MgB_2 junctions with excellent SC properties. The critical current was seen to be close to the

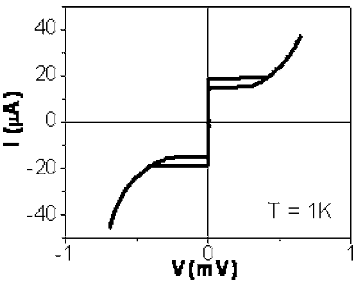

FIG. 3. Josephson pair current observed at zero bias for a MgB_2/Al_2O_3/V junction with a thinner Al_2O_3 tunnel barrier.

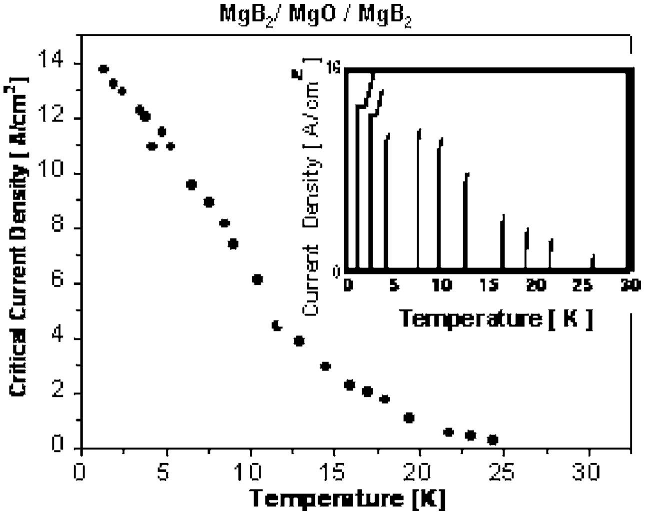

FIG. 4. Temperature dependence of Josephson current density in $MgB_2/MgO/MgB_2$ junction with $\sim 200\ \mu m^2$ junction area; Josephson current as a function of temperature for all MgB_2 tunnel junctions ($MgB_2/MgO/MgB_2$), as shown in the inset.

value of T_c of the top MgB_2 layer (28 K). A similar behavior was also observed in $MgB_2/Al_2O_3/MgB_2$ junctions with 20-Å-thick Al_2O_3 barriers. Figure 4 shows that the temperature-dependent critical current density does not follow the Ambegaokar-Baratoff theory.[18] This behavior in our junctions could result from the excess of Mg atoms between MgB_2/MgO interfaces. One of the important criteria for Josephson junction application is the product $I_C R_N$ where I_C is the Josephson critical current and R_N is the normal state resistance of the junction above the gap voltage. For a given operating frequency, it is beneficial to have as high an $I_C R_N$ value as possible.[19] An $I_C R_N$ value of ~ 4 meV was obtained for our Josephson junctions, which is comparable with π-band gap energy. This parameter is proportional to the SC gap energy, and as such, having two large gap values, Δ_π and Δ_σ, even at temperatures above 20 K, has a distinct advantage for high-speed electronics applications compared to conventional low T_C superconductors.

In summary, we investigated the SC characteristics of epitaxial $MgB_2(001)$ films using quasiparticle tunneling with a clear determination of two SC energy gaps for the π and the σ bands. Furthermore, the feasibility of the fabrication in a well-controlled manner of all MgB_2 Josephson junctions, as well as tunnel junctions with two different barriers was reported with excellent junction quality consistent with theoretical predictions. Our work on all MgB_2 junctions on Si wafers might open up possibilities for MgB_2-based high temperature superconductive electronics.

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