Magnesium-diboride ramp-type Josephson junctions

Dragana Mijatovic, Alexander Brinkman, Ingrid Oomen, Guus Rijnders, Hans Hilgenkamp,[a)] Horst Rogalla, and Dave H. A. Blank
Low Temperature Division, Department of Applied Physics, and MESA$^+$ Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

(Received 2 January 2002; accepted for publication 21 January 2002)

Josephson junctions have been realized in which two superconducting magnesium-diboride (MgB_2) layers are separated by a thin MgO barrier layer, using the ramp-type configuration. Their current–voltage characteristics follow the behavior described by the resistively shunted junction model, with an excess current of about 30% of the critical current I_c. A suppression of 70% of I_c was achieved in applied magnetic fields. Shapiro steps were observed by irradiating the junctions with 10.0 GHz microwaves, and the dependence of the step height on applied rf current is well described by a current–source model. Reference samples prepared without the MgO layer showed strong-link behavior with large I_c values. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1462869]

The remarkably high superconducting transition temperature T_c of 39 K that was discovered[1] for the noncuprate intermetallic compound MgB_2, the correspondingly large energy gap[2,3] as well as the large carrier density,[4] make this material attractive for use in superconducting electronic devices, possibly cooled by cryocoolers. To this end, the availability of high-quality thin films and Josephson junctions are essential, which triggered an intensive research in these areas.[5–20]

The realization of various Josephson devices in MgB_2 has been reported, based on, e.g., thin film nanobridges,[16] localized ion damage,[17] point contacts,[18] and thin film heterostructures with one MgB_2 electrode.[19,20] To optimally exploit the beneficial properties of MgB_2 and to be able to tune the junction characteristics by choosing the barrier parameters, the next challenging step is to realize and investigate MgB_2/artificial-barrier/MgB_2 thin film Josephson junctions.

In this letter the fabrication and characteristics of multilayer Josephson junctions with MgB_2 electrodes and a dielectric barrier is presented. The proper operation of the junctions is evidenced by a clear modulation of the supercurrent by applied magnetic fields and the occurrence of Shapiro steps under microwave irradiation.

The junctions were prepared according to the ramp-type configuration[21] (Fig. 1). First, a bilayer of MgB_2 (200 nm) and MgO (100 nm) was deposited *in situ* by pulsed laser deposition (PLD) on a MgO substrate. The MgB_2 film was prepared from a Mg-enriched MgB_2 target, using the procedure described in Refs. 10 and 15. In short, the deposition took place at 200 °C in 0.17 mbar Ar pressure for 6 min at 10 Hz, using a laser density of 4 J/cm^2. Subsequently, the MgB_2 layer was annealed at 600 °C for 5 min in a Mg plasma, generated by ablation from a Mg target in 0.22 mbar Ar. After cooling down to 200 °C, the MgO insulation layer was formed by ablating from a Mg target in an oxygen pressure of 0.5 mbar for 50 s at 10 Hz, using an energy density of 4 J/cm^2. Subsequently, the film was cooled down to room temperature keeping the pressure in the chamber unchanged. Then, a beveled edge (ramp) was defined by photolithography and argon ion beam milling, under an angle of 45°. With a beam voltage of 500 V the etching rate of the bilayer is about 8 nm/min. Due to the difference in etching rate with the photoresist a slope of the ramp of about 20° is obtained.[22] After removing the photoresist, a 12 nm MgO barrier layer was deposited by ablating Mg for 6 s at 10 Hz with an energy density of 4 J/cm^2, in 0.5 mbar O_2 at 200 °C. Subsequently, a 200 nm MgB_2 counterelectrode was deposited in the same way as the base electrode. The sample was then patterned by photolithography and ion milling to define the junctions, with an overlap of the counterelectrode of 3 μm. After sample preparation, the transition temperatures of the MgB_2 layers were typically 23 K. This reduced critical temperature as compared to the bulk value is discussed in previous articles and is attributed to the small MgB_2 grain size in these *in situ* fabricated films and to impurities, such as MgO inclusions.[10,15]

Figure 1 displays the current–voltage ($I-V$) characteristic of a 7 μm wide junction at $T=4$ K. This characteristic follows the behavior expected from the resistively shunted junction (RSJ) model, with an additional excess current of about 30% of the critical current I_c. At this temperature the I_c value is 130 μA, which implies that the junction width is

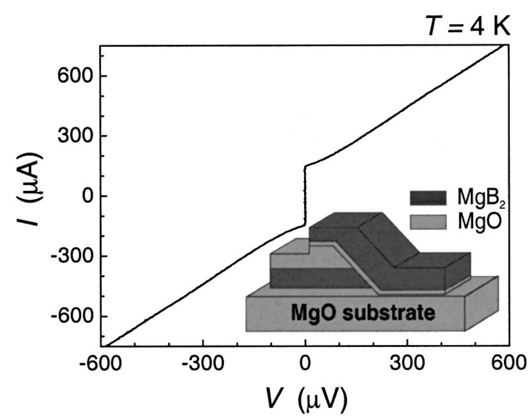

FIG. 1. Schematic of a MgB_2/MgO/MgB_2 ramp-type junction, and a measured current–voltage characteristic of a 7 μm wide junction at 4 K.

[a)]Electronic mail: h.hilgenKamp@tn.utwente.nl

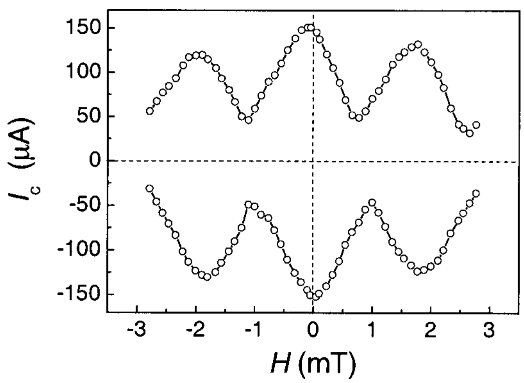

FIG. 2. Modulation of the critical current by a magnetic field applied perpendicular to the current direction and parallel to the substrate, measured at 3.4 K.

much smaller than the Josephson penetration depth. The normal state resistance R_n is almost temperature independent and has a value of about 1Ω. The I_cR_n product is 130 μV. Systematic studies of the temperature dependence of I_c and I_cR_n are in progress and will be reported elsewhere.

The application of a magnetic field H perpendicular to the current direction and parallel to the substrate resulted in a modulation of the critical current (Fig. 2). A suppression of the critical current by up to 70% was observed. The $I_c(H)$ dependence differs from the Fraunhofer dependence that is expected for a small junction with a uniform current distribution, with the large amplitude of the side peaks and the incomplete suppression of the critical current being signatures of a nonhomogeneity of the barrier.

A complete suppression of the supercurrent and the formation of Shapiro steps at multiples of $V = 20.7$ μV were observed by irradiating the junction with 10.0 GHz microwave fields at $T = 4.2$ K (Fig. 3). The voltages at which the current steps appear are as expected from the frequency of the applied radiation ν_r: $V_n = (h/2e)\nu_r n$, with $2e/h = 483.6$ MHz/μV. The modulation of the height of the Shapiro steps as a function of applied rf current is presented in Fig. 4. To describe the junction under microwave irradiation, the RSJ model is extended with a rf current–source term with a large source impedance.[23] With this current–source model a good fit to the experimental data was obtained. It is noted that the fitting parameters were the same for all the Shapiro steps. The parameter Ω, describing the ratio of the

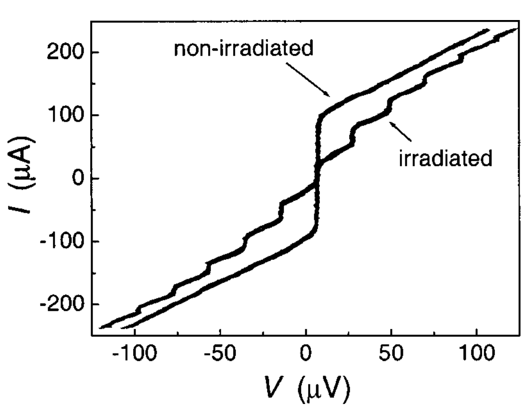

FIG. 3. Current–voltage characteristics of a 7 μm wide junction with and without 10.0 GHz microwave irradiation at $T = 4.2$ K.

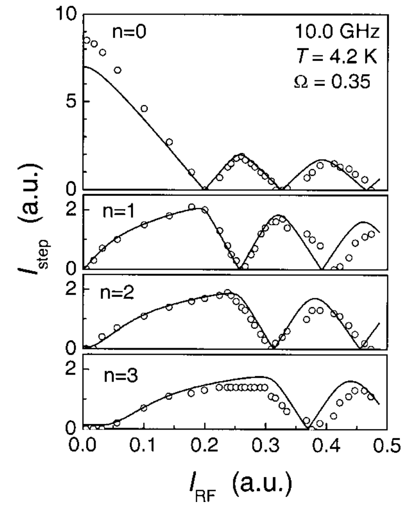

FIG. 4. Amplitude of the supercurrent and the first three Shapiro steps vs applied rf current (10.0 GHz) at $T = 4.2$ K. The solid line shows a fit using the current–source model.

fractions of rf current passing through the resistive shunt and the Josephson element was found to be 0.35.

To determine the effects of the interfaces between the MgO barrier and the electrodes on the junction transport properties, reference samples were prepared following the same fabrication procedure, except for the deposition of the barrier layer. It has been shown, e.g., in high-T_c Josephson junction technology[24] that a barrier is formed at the interface between the electrodes, due to structural damage invoked by ion milling. In contrast, for our MgB_2 ramp-type contacts this ion-milling procedure did not lead to weak link behavior. Critical currents up to 31 mA were obtained for 5 μm wide contacts at $T = 4.2$ K, which corresponds to a critical current density of 3×10^6 A/cm^2. This implies that the interface region has good superconducting properties and will not affect the transport characteristics of the Josephson junctions. Furthermore, it indicates that the ramp-type contact presents a useful configuration for via contacts in future multilayer circuits.

The nonhysteretic character of $I-V$ curves of the junctions results from the low normal state resistance and the low capacitance. The capacitance can be estimated from the junction geometry, yielding $C = 40$ fF for the junction displayed in Fig. 1. This leads to a value for the Stewart–McCumber parameter β_c of the order of 10^{-2}, which is in the nonhysteretic regime. The I_cR_n product of 130 μV at $T = 4$ K is considerably below the expectations following from the values of the energy gap in the MgB_2.[3] This is attributed primarily to barrier inhomogeneity and to the reduced critical temperatures of these *in situ* grown MgB_2 films. It is anticipated that higher I_cR_n products are attainable by improving film smoothness and enhancing the T_c.

In conclusion, all-MgB_2 ramp-type Josephson junctions with a 12 nm MgO barrier layer were realized, showing RSJ-like current–voltage characteristics. Both, dc and ac Josephson effects were demonstrated by the modulation of the Josephson current by applied magnetic fields and the appearance of Shapiro steps under applied microwave irradiation. The establishment of an all-MgB_2 Josephson junction technology, employing an artificial barrier layer of which the composition and thickness can be selected, is a further step towards electronic devices based on this superconductor.

The authors thank Frank Roesthuis, Henk-Jan Smilde, and Gerrit Gerritsma for their assistance and discussions. This work was supported by the Dutch Foundation for Research Matter (FOM) and the Royal Dutch Academy of Arts and Sciences and is part of the MESA$^+$ Strategic Orientation on Materials Science of Interfaces.

[1] J. Nagamatsu, N. Nakava, T. Muranaka, Y. Zenitani, and J. Akimitsu, Nature (London) **410**, 63 (2001).
[2] G. Kareptrov, M. Iavarone, W. K. Kwok, G. W. Crabtree, and D. G. Hinks, Phys. Rev. Lett. **86**, 4374 (2001).
[3] A. Brinkman, A. A. Golubov, H. Rogalla, O. V. Dolgov, and J. Kortus, cond-mat/0111115 (2001).
[4] W. N. Kang, C. U. Jung, K. H. P. Kim, M.-S. Park, S. Y. Lee, H.-J. Kim, E.-M. Choi, K. H. Kim, M.-S. Kim, and S.-I. Lee, Appl. Phys. Lett. **79**, 982 (2001).
[5] X. H. Zeng, A. Sukiasyan, X. X. Xi, Y. F. Hu, E. Wertz, Q. Li, W. Tian, H. P. Sun, X. Q. Pan, J. Lettieri, D. G. Schlom, C. O. Brubaker, Z.-K. Liu, and Q. Li, Appl. Phys. Lett. **79**, 1840 (2001).
[6] A. Brinkman, D. Mijatovic, G. Rijnders, V. Leca, H. J. H. Smilde, I. Oomen, A. A. Golubov, F. Roesthuis, S. Harkema, H. Hilgenkamp, D. H. A. Blank, and H. Rogalla, Physica C **353**, 1 (2001).
[7] W. N. Kang, H.-J. Kim, E.-M. Choi, C. U. Jung, and S.-I. Lee, Science **292**, 1521 (2001).
[8] C. B. Eom, M. K. Lee, J. H. Choi, L. J. Belenky, X. Song, L. D. Cooley, M. T. Naus, S. Patnaik, J. Jiang, M. Rikel, A. Polyanskii, A. Gurevich, X. Y. Cai, S. D. Bu, S. E. Babcock, E. E. Hellstrom, D. C. Larbalestier, N. Rogado, K. A. Regan, M. A. Hayward, T. He, J. S. Slusky, K. Inumaru, M. K. Haas, and R. J. Cava, Nature (London) **411**, 558 (2001).
[9] S. R. Shinde, S. B. Ogale, R. L. Greene, T. Venkatesan, P. C. Canfield, S. L. Bud'ko, G. Lapertot, and C. Petrovic, Appl. Phys. Lett. **79**, 227 (2001).
[10] D. H. A. Blank, H. Hilgenkamp, A. Brinkman, D. Mijatovic, G. Rijnders, and H. Rogalla, Appl. Phys. Lett. **79**, 394 (2001).
[11] G. Grassano, W. Ramadan, V. Ferrando, E. Belligneri, D. Marre', C. Ferdeghini, G. Grasso, M. Putti, A. S. Siri, P. Manfrinetti, A. Palenzona, and A. Chincarini, Supercond. Sci. Technol. **14**, 762 (2001).
[12] H. M. Christen, H. Y. Zhai, C. Cantoni, M. Paranthaman, B. C. Sales, C. Rouleau, D. P. Norton, D. K. Christen, and D. H. Lowndes, Physica C **353**, 157 (2001).
[13] C. Buzea and T. Yamashita, Supercond. Sci. Technol. **14**, R115 (2001).
[14] K. Ueda and M. Naito, Appl. Phys. Lett. **79**, 2046 (2001).
[15] D. Mijatovic, A. Brinkman, G. Rijnders, H. Hilgenkamp, H. Rogalla, and D. H. A. Blank, Physica C (submitted).
[16] A. Brinkman, D. Veldhuis, D. Mijatovic, G. Rijnders, D. H. A. Blank, H. Hilgenkamp, and H. Rogalla, Appl. Phys. Lett. **79**, 2420 (2001).
[17] G. Burnell, D.-J. Kang, H. N. Lee, S. H. Moon, B. Oh, and M. G. Blamire, Appl. Phys. Lett. **79**, 3464 (2001).
[18] Y. Zhang, D. Kinion, J. Chen, D. G. Hinks, G. W. Crabtree, and J. Clark, Appl. Phys. Lett. **79**, 3995 (2001).
[19] G. Carapella, N. Martucciello, G. Costabile, C. Ferdeghini, V. Ferrando, and G. Grassano, cond-mat/0108212 (2001).
[20] M. H. Badr, M. Fremat, Y. Sushko, and K.-W. Ng, cond-mat/0110421 (2001).
[21] J. Gao, W. A. M. Aarnink, G. J. Gerritsma, and H. Rogalla, Physica C **171**, 126 (1990).
[22] D. H. A. Blank and H. Rogalla, J. Mater. Res. **12**, 2952 (1997).
[23] See, e.g., A. Barone and G. Paterno, *Physics and Application of the Josephson Effect* (Wiley, New York, 1982); K. K. Likharev, *Dynamics of Josephson Junctions and Circuits* (Gordon and Breach, New York, 1986).
[24] B. H. Moeckly and K. Char, Appl. Phys. Lett. **71**, 2526 (1997).