Planar MgB_2 Josephson junctions and series arrays via nanolithography and ion damage

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We have fabricated planar thin-film MgB_2 Josephson junctions and 20-junction series arrays using 200-keV ion implantation and electron-beam lithography. Resistively shunted junction *I-V* characteristics were observed in the temperature range of 34–38 K. The ac Josephson effect was observed and flat giant Shapiro steps in arrays suggest good junction uniformity with a small spread in junction parameters. The temperature dependence of the critical current suggests that the nature of the interface between the superconductor and normal region can be described using a soft boundary proximity effect coupling model. We believe that the higher operating temperature and close spacing of these junctions make them promising candidates for quantum voltage standards and other devices. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2162669]

Closely packed series arrays of nonhysteretic Josephson junctions are desired for many applications, such as quantum voltage standards,[1] arbitrary wave-form generators,[2] microwave oscillators,[3] etc. These devices require hundreds or even thousands of junctions with uniform I_cR_n products, where I_c is the critical current and R_n is the normal resistance in the resistively shunted junction (RSJ) model.[4,5] Uniform I_cR_n is essential so that all of the junctions in the array produce a Shapiro step for the same bias current, which results in a giant Shapiro step. It is also of great benefit for the junction array to appear as a lumped element, which requires the size of the array to be smaller than 1/4 of the wavelength of the rf drive frequency. For a 1 V standard, driven at 18 GHz, this requires 13 500 junctions with 120 nm spacing.[6] This spacing to our knowledge has only been realized in Nb–$MoSi_2$–Nb stack junctions[7] and $YBa_2Cu_3O_{7-\delta}$ (YBCO) planar ion damage junctions. The uniformity and quality of the Nb junction stacks is outstanding, however due to the low T_c of Nb, their operating temperature is usually only 4.2 K. Higher operating temperatures have been obtained using YBCO junctions; however, arrays of more than ten junctions have not been achieved yet due to nonuniform junction properties.[8,9] There is considerable interest in fabricating Josephson junctions and arrays from magnesium diboride (MgB_2) thin films because its T_c of 41 K is much higher than that of niobium and its longer coherence length (in comparison to YBCO) provides a better chance of making uniform junctions. For devices cooled with cryocoolers, MgB_2's higher T_c has significant advantages. A recent survey of 235 cryocoolers[10] reveals many potential benefits from MgB_2 devices. For a 300 mW cooler, the input power to the cooler can be up to 100 times less for an MgB_2 device operating at 37 K compared to niobium at 4.2 K. Furthermore, the cooler mass decreases by 10 times and the cost is approximately halved.

Other groups have already demonstrated various types of MgB_2 junctions, ramp junctions,[11,12] nanobridges,[13] and ion damage junctions.[14] Ramp junctions cannot meet the close spacing requirements for lumped element devices and the other techniques rely on focused ion beam processing, which is not practical for the reproduction of large numbers of junctions. The highest demonstrated operating temperature of these other junction types is 25 K,[14] which is well below our reported temperature of 37.5 K. Furthermore, these junctions have yet to demonstrate the reproducibility of uniform junction parameters necessary for multijunction arrays. In this letter, we demonstrate a MgB_2 junction array technology that can meet the aggressive spacing requirements and uniformity requirements for lumped element devices with operating temperatures above 37 K.

MgB_2 thin films, 100 nm thick, were grown on SiC-4H(0001) substrates using hybrid physical-chemical vapor deposition (HPCVD). The HPCVD technique has been described in detail elsewhere.[15] The films had a bulk T_c of over 39 K. After deposition, the films were coated with 200 nm of sputtered gold to serve as a contact layer and to protect the film from degradation during subsequent processing. Contact pads and 4 μm wide, four-point bridges were patterned using contact photolithography and liquid nitrogen cooled Ar ion milling. After patterning, photolithography was repeated to remove the Au from the device area with Ar ion milling while leaving it over the contact pads. Device fabrication was carried out using a technique we developed for YBCO junctions.[16] Patterned films were spin-coated with 800 nm of positive photoresist followed by a deposition of 25 nm of thermally evaporated Ge. A thin layer of 100 nm of poly(methylmethacrylate) (PMMA) was coated on top of this structure and electron beam lithography was used to scribe 80-nm lines in the PMMA where the junction barriers were to be formed. The developed lines in the PMMA were transferred into the Ge using a fluorocarbon reactive ion etch (RIE). The slow etch rate of Ge in O_2 plasma allows it to serve as an

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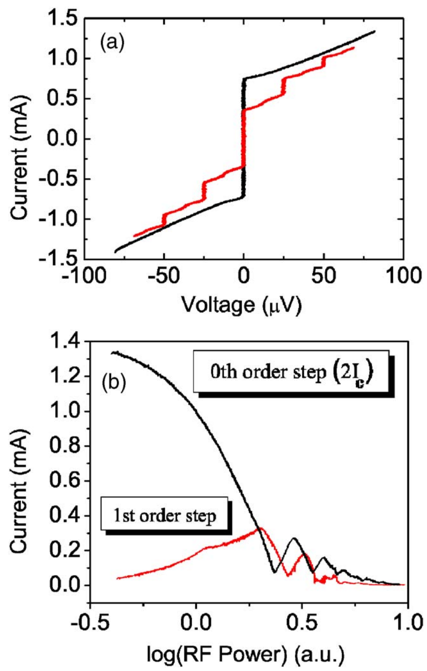

FIG. 1. (Color online) (a) *I-V* characteristics for a single junction measured at 37.2 K, with and without 12 GHz microwave radiation. (b) Microwave power dependence of the critical current and first-order Shapiro step.

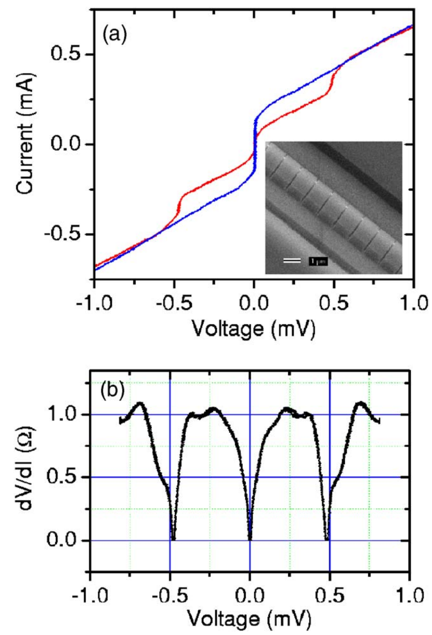

FIG. 2. (Color online) (a) *I-V* characteristics for a 20-junction array measured at 37.5 K, with and without 12 GHz microwave radiation. The inset is a scanning electron microscope photograph of an ion implantation mask after etching used to create a multijunction array. (b) Differential resistance vs voltage measured under the same radiation.

etch mask for the underlying polymer, which was slowly etched in a low pressure O_2 RIE plasma. After etching, the samples were bombarded with 200 kev Ne^+ with a dose of 1×10^{13} ions/cm^2 at a 7° tilt to the normal to limit channeling effects. It has been shown that ion damage of MgB_2 reduces T_c and increases resistivity.[17] Monte Carlo simulations[18,19] showed the thickness of the mask to be sufficient in blocking ions from damaging the film beneath unetched areas. Furthermore, simulations also have shown that the 200-keV ions are of sufficient energy to penetrate the MgB_2 film creating a uniform damage region of reduced T_c, which serves as the junction barrier. Eight single junctions and eight 20-junction series arrays with interjunction spacing of 1 μm were fabricated on a single chip using this method.

Figure 1(a) shows *I-V* measurements for a single junction measured at 37.2 K, with and without 12 GHz microwave radiation. The *I-V* characteristics were RSJ-like with an I_cR_n product of 75 μV. They did not exhibit rounding near I_c for $T \ll T_c$, as observed in YBCO ion damage junctions.[9] We believe this is an indication that the Josephson vortices are larger than the bridge width for temperatures ranging from T_c to 4.2 K. The normal state resistance is about 0.1 Ω and is approximately the same as YBCO junctions fabricated under the same conditions; however, I_c is about an order of magnitude higher. Under microwave radiation Shapiro steps are visible in the *I-V* characteristic at the expected voltages: $V=nhf/2e$ and half-integer Shapiro steps appear when the junctions are measured at temperatures where I_c is greater than 0.75 mA. This may be due to magnetic flux generated from the bias or from a nonsinusoidal Josephson current relation. Figure 1(b) shows the power dependencies of the critical current and first-order Shapiro step. This was measured using a sample and hold circuit to record the step height as rf power was swept. The Bessel-like dependence is a clear indication of the ac Josephson effect.

Figure 2(a) shows the *I-V* characteristics for a 20-junction series array measured at 37.5 K, with and without 12 GHz microwave radiation. A flat giant Shapiro step is visible at 20 times the value of a single junction. This leads us to believe that the spread in I_cR_n is small; however, rounding near I_c suggests some spread in I_c and room for improvement. Differential resistance was measured under the same conditions [Fig. 2(b)]. dV/dI reaching zero confirms that the step is flat (e.g., all junctions are locked to the 12 GHz drive signal). Cooling to lower temperatures increases the critical current of the junction but does not increase the amplitude of the Shapiro step. We attribute this to an increase in excess non-Josephson current.

The critical current as a function of temperature was determined for a single junction by recording *I-V* characteristics at different temperatures (Fig. 3). Because there is no chemical or structural boundary between the undamaged and damaged regions, we describe the boundary as a soft boundary which is determined by the proximity effect. This boundary will spatially move as a function of temperature or bias current. Evidence for this is that the temperature dependence follows $I_c \propto (T-T_c)^3$ near T_c. The derivation of this dependence for this type of boundary has been previously reported for ion damage YBCO junctions.[20] At lower temperatures, $I_c \propto (T-T_c)^2$ indicates that the boundary can be described as a "rigid" deGennes superconductor normal metal interface (S/N). Resistance as a function of temperature measured using a 10 μA bias [Fig. 3(a)] shows the T_c of the bulk material to be 38.8 K and the T_c of the weak link to be 38.2 K. This reduction in T_c (≈0.6 K) is approximately one order of magnitude smaller than for YBCO junctions (≈6 K) fabricated with identical conditions. This indicates that the T_c of YBCO is more sensitive to ion damage than is MgB_2. The nature of the disorder will receive further study.

In conclusion we have fabricated planar ion damage MgB_2 Josephson junctions and arrays. The higher operating

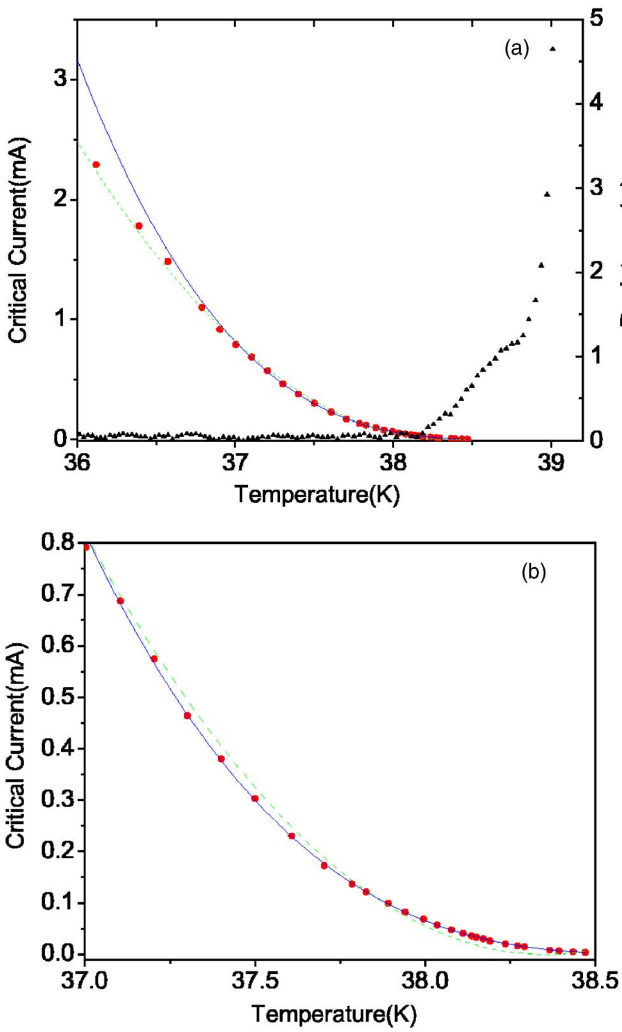

FIG. 3. (Color online) (a) Single-junction critical current (circles) and resistance (triangles) temperature dependencies. The dashed and solid lines are fits with $I_c \propto (T-T_c)^2$ and $I_c \propto (T-T_c)^3$, respectively. (b) The same data shown for a temperature range near T_c.

temperature of these junctions, in comparison to Nb, simplifies cooling requirements and substantially decreases cryocooler input power. Uniformity of junction parameters within the arrays was sufficient to achieve phase locking to an applied microwave signal. Differential resistance measurements confirmed the flatness of observed giant Shapiro steps. The temperature dependence of the critical current in these junctions is similar to ion damage YBCO Josephson junctions. We believe this junction technology is a good candidate for quantum voltage standards and simular devices that can function at temperatures above 35 K.

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