Step-edge fabrication of ultrasmall Josephson microbridges

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A technique for producing ultrasmall variable-thickness Josephson microbridges for high-frequency applications is described. A two-dimensional shadowing technique is employed with self-aligning photolithographic and reactive-ion milling processes to pattern the substrate with high-resolution steps. Step heights normal to the substrate are used to determine microbridge dimensions. Lead-alloy microbridges with resistances $\approx 10\,\Omega$ and dimensions of 50 nm have been produced, and their electrical properties studied. The limits on device size are in the range 10–20 nm. Heated-substrate deposition of high-T_c superconductors is compatible with this technique.

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In recent years, Josephson-effect devices have demonstrated considerable promise as low-noise mixers and detectors in the millimeter and submillimeter wavelength region.[1] The best performance has been achieved with point contacts, for which direct, fundamental-frequency detection to 2.5 THz[2] and bolometric mixing to 31.5 THz[3] have been observed. Unfortunately, most point contacts are mechanically unstable, do not tolerate thermal cycling, or fail to achieve the full value of the $I_c R_n$ product needed for full frequency response. These weaknesses, and the desire to produce integrated receivers and Josephson-junction arrays, have stimulated extensive efforts to develop superconducting microbridges, the thin-film analog of the point contact. To date these efforts have not been fully successful and the high-frequency performance of microbridges has fallen short of that obtained with point contacts.[1] The limitations on performance have been primarily results of Joule self-heating,[4,5] although relaxation-time effects can also limit the temperature and voltage (frequency) range of operation.[6] Above ≈ 100 GHz, a severe limitation on microbridge performance is also posed by the generally low device impedance, $< 1\,\Omega$, which prevents efficient radiation coupling. For good coupling, resistances $\geqslant 10\,\Omega$ are required.[7]

A remedy to the limitations on microbridge performance listed above is to incorporate the three-dimensional cooling of the point contact by using the variable-thickness configuration, while reducing the microbridge size to approach that of point contacts, in the range 10–20 nm.[4] This increases the resistance, reduces the effects of self-heating, and keeps the size comparable to the coherence length as required for near-ideal Josephson behavior.[6,8] However, fabrication techniques have not been available to accomplish this, and the smallest microbridges which have been studied to date have been 120 nm in length.[6,9] In this letter we report a new fabrication technique, step-edge lithography,[10] for production of variable-thickness microbridges with dimensions $\leqslant 100$ nm. The microbridge devices produced achieve both the good cooling and the high electrical resistance required for efficient high-frequency operation.

The step-edge lithography technique utilizes two-dimensional shadowing to produce a metal-film pattern with very fine details. Using this metal film as a mask, the pattern is ion milled into the substrate. The microbridge is deposited on the edge of a substrate step, so that step heights determine microbridge dimensions. The technique may be illustrated by considering the process sequence shown in Fig. 1 for a bridge 50 nm wide, 25 nm thick, and 100 nm long, with pads (banks) 200 nm thick. In this example we shall assume that the metal atoms stick at the exact point of impact. This idealized ray-optics picture is a standard assumption for most shadowing processes. Deviations from this model and result-

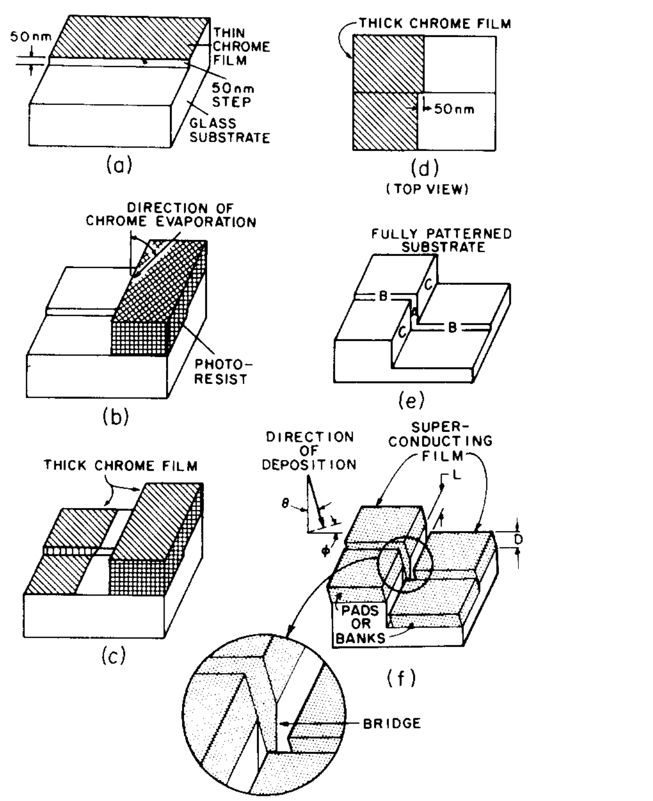

FIG. 1. Fabrication procedures of the step-edge lithography technique, for making a variable-thickness superconducting microbridge with a width W of 50 nm, length L of 100 nm, and pad thickness D of 200 nm. Details of the processes are given in the text. Chrome film is single hatched, photoresist is cross hatched, and superconducting metal film [Fig. 1(f)] is dark. Dimensions are not to scale. The diagram is drawn for the small ϕ limit, so the bridge thickness $d \ll D$ is not shown.

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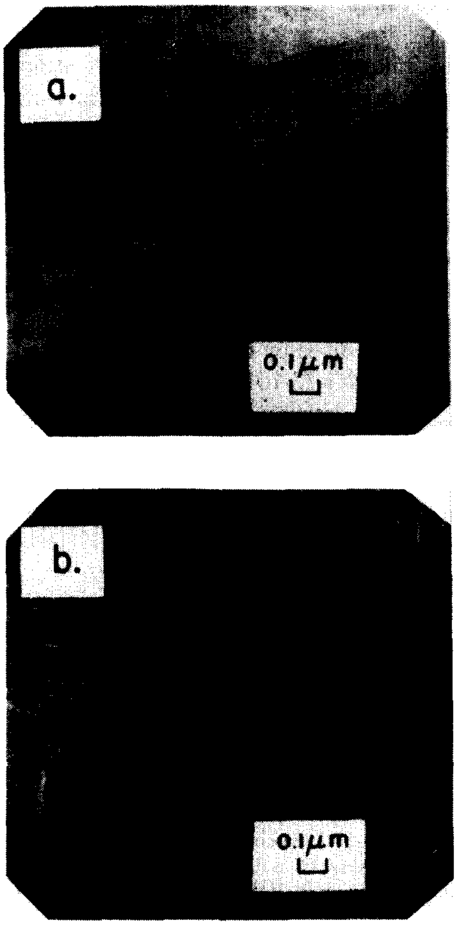

FIG. 2. Scanning electron micrograph of a microbridge [Fig. 2(a)] and a step edge [Fig. 2(b)] fabricated with the procedures of Fig. 1. A 0.1-μm size scale is shown. Perspective is like that for Fig. 1(f). The light regions in Fig. 2(a) are the superconducting metal film, and the dark regions are the edge of the substrate step which is not coated [regions C in Fig. 1(e)]. Dimensions of the bridge are $d = L = 60$ nm, $W_{min} = 50$ nm, and $D = 240$ nm. The step height is 300 nm. (Dimensions cannot be determined directly from the micrographs due to foreshortening at this observation angle.)

ing fabrication limits will be discussed later. Also, in Fig. 1 we assume for simplicity that the chrome masking films are unaffected by the ion milling process. For the measured milling rates this is reasonably accurate.

(a) A 50-nm step is ion milled into the glass substrate. A thin 20-nm chrome film, patterned by conformal-photolithography techniques,[11] is used as the milling mask. A CF_4 reactive-ion milling beam is used to enhance the milling rate of the substrate.[12,13] The chrome film is removed by chemical etching.

(b) A second stage of photolithography, using through-the-substrate projection exposure,[14] leaves a half-plane of photoresist whose edge is perpendicular to the initial step. A sharp edge profile is obtained. The top surface of the photoresist is smooth over the step, due to the spin-on application.

(c) A 100-nm chrome film is then evaporated at an angle of 45° from the substrate normal, producing a sharp shadow of the photoresist edge. Because the photoresist is thicker over the bottom of the step, the chrome shadow there falls further back from the photoresist edge than on the top of the step. The edge of the chrome film on the left therefore has a sharp jog in it. [See Fig. 1(d).] The length of the jog is equal to the height of the initial step, 50 nm. Thus a height dimension has been "folded over" onto the substrate, a key part of the process.

(d) The photoresist and the chrome film overlying it are stripped in acetone, leaving the chrome film on the left half of the substrate.

(e) The half of the substrate unprotected by the chrome pattern is ion milled to a depth of 300 nm. The chrome film is then removed by chemical etching to reveal the fully patterned substrate shown in Fig. 1(e). The microbridge will be formed in region A, the two pads or banks in regions B.

(f) A superconducting film is evaporated to coat regions A and B of the substrate [Fig. 1(e)], but not regions C. With the evaporation direction as shown, the bridge-film thickness (on the face of the jog, region A) is given by $d = D \tan\Theta \sin\phi$, with D the bank thickness, Θ the coaltitude angle of the evaporation direction, and ϕ the azimuth angle. To form a 25-nm-thick bridge with 200-nm-thick banks, we choose $\Theta = 20°$ and $\phi = 20°$.

With this fabrication technique all microbridge dimensions are determined by step or film heights and the evaporation angle. The bridge width W is approximately equal to the width of the jog and thus to the height of the first step. The bridge length L is equal to the height of the deep step minus the pad thickness. The bridge thickness is determined by the evaporation direction and the thickness of the banks. Thus, although optical lithography is employed, device dimensions are *not* limited by optical diffraction, and can be extremely small.

A $Pb_{0.9}In_{0.1}$ microbridge produced with this technique, number S-6, is shown in Fig. 2(a). Its dimensions are approximately $d = L = 60$ nm and $D = 240$ nm. W tapers from 90 to 50 nm at the narrowest point. (The SEM viewing angle is at a substrate tilt of 45°.) These dimensions, which are typical of the dozen microbridges produced to date, were determined from a series of electron micrographs at different viewing angles.

The observed microbridge dimensions and shape are close to those predicted by the idealized deposition assumptions of Fig. 1, but fine details of film topography, increasingly significant as dimensions are reduced below 100 nm, depend on surface energy considerations in violation of the ray-optics model. Agglomeration of the device film has been minimized by use of an alloy superconductor (Pb-In) and deposition at 77 K, but even with these precautions, the actual length of the smallest bridges systematically exceeds the idealized expectation. Similar effects lead to edge roughness and pattern distortion in the thick Cr mask film. Since defects in the mask film are reproduced in the resulting step edge, Cr masks yield reproducible microbridges only down to $W \approx 50$ nm.

Our recent results with mask films of Ni-Cr alloy indicate that smoother edges and more accurate shadowing are indeed obtained, making possible bridge widths < 50 nm. Further improvements in dimensional reproducibility, as well as smaller lengths, should be possible with refractory superconducting films, such as Nb, which have finer grain size.[9] Reactive-ion sputter etching[13] achieves greater etch-rate differences than the present reactive-ion milling, and should thus allow the use of thinner masking films, also with smaller grain size.

In obtaining bridge dimensions < 50 nm, the squareness of the step does not appear to be a limiting factor. In Fig. 2(b), which shows a bare 300-nm step, the radius of curvature at the top and bottom corners is < 20 nm; there is no evidence of faceting or redeposition. We therefore believe that with modification of the present technique (e.g., use of finer-grain superconducting and masking films), it will be possible to achieve device sizes of 10–20 nm. This indeed approaches the inferred size of high-performance point contacts.

The electrical performance of bridge *S*-6, the microbridge shown in Fig. 2a, is typical of the eight step-edge bridges tested to date. For bridge *S*-6, the normal-state resistance $= 6.8\ \Omega$. (We define R_n as the minimum differential resistance at $T = 0.99\ T_c$, which excludes the resistance of the banks and avoids the effects of Joule heating.) The *I-V* curve remains nonhysteretic to $\Delta T = T_c - T \approx 1.0$ K ($T_c = 7.0$ K) and steps in the *I-V* curve due to 25 GHz microwave irradiation are observed to 1.4 mV. This corresponds to a Josephson oscillation frequency of 700 GHz. For comparison, the best uniform-thickness Pb-In bridge produced in this laboratory, for which $R_n = 5.5\ \Omega$, was nonhysteretic only for $\Delta T < 0.15$ K and showed steps to only 0.4 mV.[14] Clearly, the improved cooling associated with small size and variable-thickness geometry is significant. The best variable-thickness Sn bridge reported by Octavio *et al.* showed microwave steps to 3.7 mV, but its normal-state resistance was only 0.3 Ω.[4] Thus, although the Sn bridge showed better voltage response, its low resistance in practice prohibits efficient, broadband coupling at microwave frequencies, and makes even resonant coupling difficult at frequencies above ≈ 100 GHz.

The fabrication technique described here offers a number of advantages over other current techniques. First, it is self-aligning and has excellent resolution. Second, large aspect ratios of pad thickness to bridge length, D/L, can be achieved, and with a single superconducting film deposition. Third, the substrate can be heated during deposition, as required for deposition of high-T_c superconductors and sometimes for Nb films. Also, no processing is required after depostion, so processing damage[15] to these high-T_c films is avoided. Finally, the step-edge technique is relatively simple, and may be easily implemented.

The fabrication technique described can be extended to produce bridges and banks of different materials, by deposition from two sources at different angles. One can thus produce S-N-S structures, which are particularly attractive for use with high-T_c A-15 superconductors.[15] Another extension of these techniques would use a square-wave grating structure, instead of the single deep step, to produce series microbridge arrays.

The step-edge technique, therefore, allows fabrication of Josephson microbridges in a wide variety of materials and configurations. 50-nm microbridges of Pb-In alloy have been produced, and these devices have electrical characteristics appropriate for high-frequency applications. In addition, the basic step-edge technique may be employed to produce various other useful microstructures with dimensions $\leqslant 50$ nm, such as x-ray masks on SiO_2 windows,[16] and very small all-refractory tunnel junctions (e.g., Nb_3Sn).

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[1]See AIP Conf. Proc. **44**, (1978), for a recent review of Josephson-effect device applications.

[2]D.A. Weitz, W.J. Skocpol, and M. Tinkham, J. Appl. Phys. **49**, 4873 (1978).

[3]D.G. McDonald, F.R. Petersen, J.D. Cupp, B.L. Danielson, and E.G. Johnson, Appl. Phys. Lett. **24**, 335 (1974).

[4]M. Tinkham, M. Octavio, and W.J. Skocpol, J. Appl. Phys. **48**, 1311 (1977); M. Octavio, W.J. Skocpol, and M. Tinkham, IEEE Trans. **MAG-13**, 739 (1977).

[5]Li-Kong Wang, Alessandro Callegari, Bascom S. Deaver, Jr., Daniel W. Barr, and Robert J. Mattauch, Appl. Phys. Lett. **31**, 306 (1977).

[6]John Warlaumont, J.C. Brown, and R.A. Buhrman, Appl. Phys. Lett. **34**, 415 (1979).

[7]P.L. Richards, in *Semiconductors and Semimetals*, edited by R.K. Willardson and A.C. Beer (Academic, New York, 1977), Vol. 12, p. 395.

[8]In general the microbridge size must be comparable to or less than the superconducting coherence length for ideal Josephson behavior; see K.K. Likharev, Rev. Mod. Phys. **51**, 101 (1979). A possible exception is the case of granular superconductors, where tunneling between grains may lead to nearly ideal Josephson behavior even in large microbridges; see G. Deutscher and R. Rosenbaum, Appl. Phys. Lett. **27**, 366 (1975).

[9]R.B. Laibowitz, A.N. Broers, J.T.C. Yeh, and J.M. Viggiano, Appl. Phys. Lett. **35**, 891 (1979). For 120 nm length, $I_c R_n$ is only 0.3 mV.

[10]R.H. Havemann, J. Vac. Sci. Technol. **15**, 389 (1978); and M. Heiblum, S.Y. Wang, J.R. Whinnery, and T.K. Gustafson, IEEE J. Quantum Electron. **QE-14**, 159 (1978), have reported the use of film edges for producing oxide-barrier tunnel diodes.

[11]Henry I. Smith, Frank J. Bachner, and N. Efremow, J. Electrochem. Soc. **118**, 821 (1971).

[12]Ion gun is Commonwealth Scientific Model 2-30, operated at 5 kV. The milling rate for the chrome film with CF_4 milling gas is approximately $\frac{1}{5}$ that of the microscope cover-glass substrate. The use of CF_4 is suggested by its successful use for reactive-ion sputter etching, Ref. 13.

[13]H.W. Lehmann and R. Widmer, J. Vac. Sci. Technol. **15**, 319 (1978).

[14]M.D. Feuer, D.E. Prober, and J.W. Cogdell, AIP Conf. Proc. **44**, 317 (1978); M.D. Feuer and D.E. Prober, IEEE Trans. **MAG-15**, 578 (1979), and unpublished.

[15]R.B. van Dover, R.E. Howard, and M.R. Beasley, IEEE Trans. **MAG-15**, 574 (1979).

[16]D.C. Flanders and Henry I. Smith, J. Vac. Sci. Technol. **15**, 1001 (1978); D.C. Flanders, Proceedings of the Fifteenth Symposium on Electron, Ion, and Photon Beam Technology, J. Vac. Sci. Technol. (to be published).