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plasma to cool and for the onset of line emission); (2) the preference for operation at high pressures (the electron cooling rate increases with increasing pressure); (3) the particular spatial position giving maximum laser output (in the cooler outer regions of the expanded plasma); (4) the fact that the dominant source of emission in the afterglow for similarly produced plasmas has been shown to result from electron-ion recombination[4]; (5) the presence of strong laser action at 2.03 μm in xenon and the absence of laser action at 3.5 μm (normally strong[5] with dc or rf excitation). The dominance of the 3.5-μm line over the 2.03-μm line in a dc discharge probably results from the fact that the upper laser level for the 3.5-μm line is lower in energy (but from the same configuration) than that of the 2.03-μm upper level, and, as a consequence, would be more highly populated via electron excitation. In contrast, in a laser-produced plasma where excitation comes from the recombining ion, the 2.03-μm upper level would be populated more readily than the 3.5-μm upper level.

[1]W. T. Silfvast, L.H. Szeto, and O.R. Wood II, Bull. Am. Phys. Soc. 21, 1061 (1976).

[2]L. I. Gudzenko and L. A. Shelepin, Zh. Eksp. Teor. Fiz. 45, 1445 (1963) [Sov. Phys.-JETP 18, 998 (1964)].

[3]W. T. Silfvast and O. R. Wood II, Appl. Phys. Lett. 25, 274 (1974).

[4]J. M. Green, W. T. Silfvast, and O. R. Wood II, J. Appl. Phys. 48, 2753 (1977).

[5]C. S. Willett, in *Handbook of Lasers*, edited by R. J. Pressley (Chemical Rubber, Cleveland, 1971), pp. 210—236.

[6]L. I. Gudzenko, L. A. Shelepin, and S. I. Yakovlenko, Sov. Phys.-Usp. 17, 848 (1975).

Offset masks for lift-off photoprocessing

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We describe a technique using photolithography to produce submicron-scale thin-film structures and simple multilevel structures by single-mask lift-off processing. The technique employs masks offset from the substrate and oblique angle thin-film deposition. It provides a simple means of making small-area Josephson junctions and varying-thickness superconducting bridges and is suitable for the inclusion of these devices in circuits. The examples we show emphasize such applications in superconductivity; however, the technique may find uses in other fields as well.

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For thin-film devices requiring micron or submicron dimensions, satisfactory photoresist masks are generally difficult to make or are simply inadequate. This is especially true for multilevel devices which require precise interlevel registration. The technique described here uses photolithography in a novel way to produce submicron device features and allows single-mask fabrication of some simple multilevel devices. We have found that a procedure recently developed by Dunkleberger[1] for "lift-off" processing of thin-film circuits allows the suspension of reasonably large segments of a resist mask a known distance from a substrate. In lift-off processing,[2-4] films are patterned by evaporating through openings in a mask which is later removed or "lifted off" along with the masked-off portions of the film. Usually, deposition at normal incidence is required in order to provide a clean break between the parts of the film on the substrate and on the mask. With masks offset from the substrate, normal-incidence deposition is not necessary to achieve lift-off. As shown in Fig. 1, one may vary the deposition angle to obtain several kinds of useful alterations of the mask's image as represented in the film pattern on the substrate.

Figure 1(a) sketches in cross section an opening in the kind of mask considered here. The mask consists of a support layer of resist having thickness δ_1 and an overlying resist layer which contains the pattern information and has a comparable thickness δ_2. As suggested in Fig. 1(a), a narrow ($W_0 \sim \delta_1, \delta_2$) opening can be used to produce a device line which is significantly displaced and reduced in width relative to the mask opening by evaporating a film at an angle θ relative to normal incidence. In fact, for a sufficiently large angle, $\theta > \theta_c \equiv \tan^{-1} W_0/\delta_2$, the line can be "closed", i.e., no device line will appear. Similarly, with two depositions a narrow space between mask openings [Fig. 1(b)] can be used to produce a thin-film device gap which is narrower than the mask feature or is "closed", yielding a joint between the subsequently deposited films. For our masks, a narrow space between mask openings is simply a bar of resist supported from its ends and clearly cannot be indefinitely long. One may also selectively close orthogonal lines and gaps if one varies not only θ but also the deposition azimuth ϕ. For example, Fig. 1(c) represents a top

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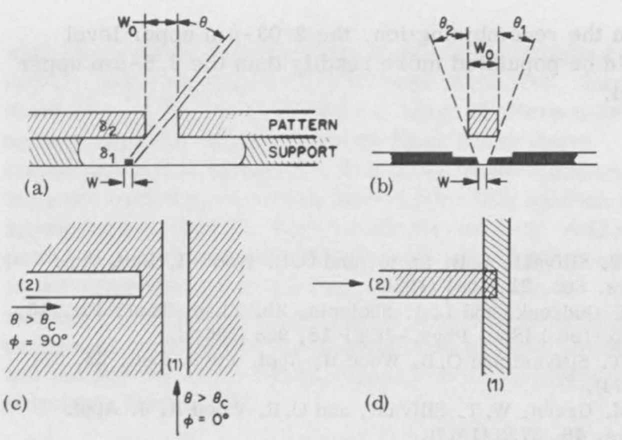

FIG. 1. Outline of procedures employing photoresist masks with elements suspended above the substrate combined with film deposition at directions defined by angles θ and ϕ. (a) A mask opening yields a narrow line. (b) A space between openings yields a gap of reduced width. (c) Two orthogonal mask openings yield two independently deposited device lines (d).

view of two narrow orthogonal mask openings. Deposition with $\theta > \theta_c$ and at the indicated azimuths will yield two separate lines which are joined as shown in Fig. 1(d). The registration between the lines is automatic in that it is determined primarily by the registration of the corresponding mask elements and by the deposition angles which may be set with arbitrary precision.

The practicality of the sort of shadowing depicted in Fig. 1 depends on the possibility of making masks reasonably similar to the idealizations in Fig. 1. Specifically, one requires that δ_1 and δ_2 be known and that the mask-edge profile be well defined, preferably rectangular as shown in Fig. 1. It is also implicitly assumed that one is concerned with mask features already small, i.e., comparable to δ_1 and δ_2. Dunkleberger's procedure[1] yields satisfactory masks and is outlined below.

Using one of the positive AZ1350 Shipley resists, the support layer is spun on the substrate and blanket exposed so as to be everywhere soluble in the resist

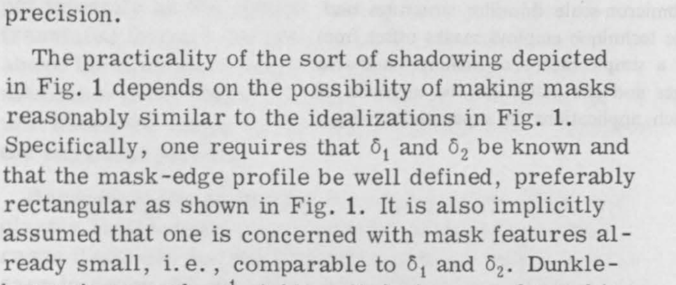

FIG. 2. (a) A 1.3-μ opening in an AZ1350J pattern layer; $\delta_1 = \delta_2 = 1.5\ \mu$. (b) Two narrow gold lines produced using this mask. Deposition directions are suggested by the arrows in (a). The markers are 1 μ. Vertical distances are foreshortened since this and the following micrographs were made with the samples tilted forward.

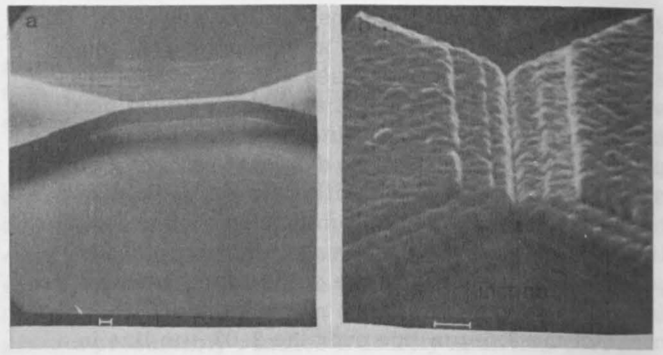

FIG. 3. (a) A bridge of resist $1.5 \times 1.5 \times 10\ \mu$ and suspended 1.5 μ above the substrate. (b) A small-area Josephson junction formed from such a mask. The perspective is rotated by 90° relative to (a). The markers are 1 μ.

developer. Next, a "separation layer" of aluminum is evaporated on the resist layer. The separation layer's only role is to protect the support layer which would otherwise dissolve when applying the next layer of resist. Consequently, a thin ($\ll \delta_1, \delta_2$) aluminum layer suffices. After spin on of the second layer of resist, it may be patterned and developed in the usual way. Parts of the separation layer exposed by mask openings must be removed in a suitable etchant. Then the substrate is reimmersed in the developer until the support layer is dissolved to the extent desired. This procedure yields an "undercut" mask profile like that sketched in Fig. 1(a). The undercut may be optically inspected if a semitransparent separation layer has been used.

Figures 2–5 show scanning electron micrographs of masks of the resist AZ1350J (both layers) and thin-film structures made using the masks. The masks were patterned by contact printing from masters supplied by the Bell Laboratories Electron Beam Exposure System.

Figure 2(a) shows a mask with $\delta_1 = \delta_2 = 1.5\ \mu$ and having a 1.3-μ opening. Two depositions at different oblique angles (roughly indicated by the arrows) produced the gold lines shown in Fig. 2(b). The linewidths are about 0.25 and 0.5 μ. The smaller width is almost the lower limit attainable given the roughness of the mask walls and also approximates the typical linewidth error (mask to mask) for good masks.

Figure 3(a) shows a $1.5 \times 1.5 \times 10$-μ bar of resist

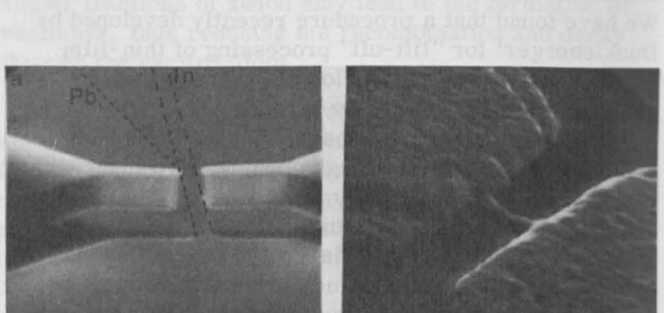

FIG. 4. (a) A mask used for fabrication of varying-thickness superconducting microbridges. (b) An indium bridge with banks of indium overlaid with Pb. The markers are 1 μ.

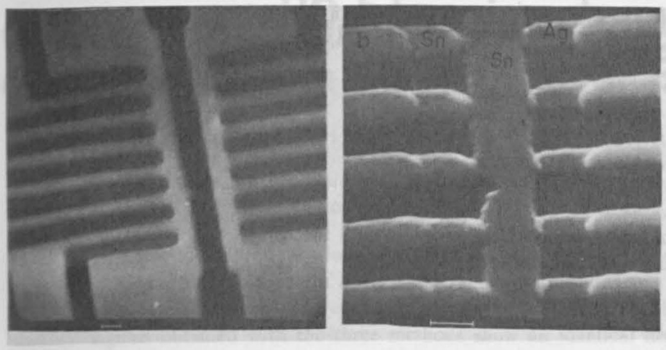

FIG. 5. (a) This mask is suspended above the substrate for most of the area shown. (b) A sample made using the mask and three depositions. The markers are 1 μ.

suspended 1.5 μ above a substrate with the supports just discernible at the bar ends. This simple mask element can be used to produce a narrow gap as suggested in Fig. 1(b). Figure 3(b) shows a Josephson junction formed by two depositions from opposing angles with an intermediate oxidation step. A third (superfluous) deposition from normal incidence provides an additional "shadow" of the resist bridge. The general topology shown is suitable for wide varying-thickness superconducting bridges as well as Josephson junctions. In these applications, the procedures used are similar to those of Niemeyer,[5] who used a thin fiber laid across a substrate groove as a shadow mask for the fabrication of isolated devices.

Figure 4(a) shows one alternative for making narrow varying-thickness bridges. This time there is a 1-μ break in the resist bridge. For the device shown in Fig. 4(b), indium was deposited at an oblique angle to narrow the bridge. Lead deposited at an even greater angle, so that the break in the bridge was "closed", only built up the banks. The bridge could have been shortened as well as narrowed by a procedure involving one more lead deposition at a comparable elevation but with the azimuth adjusted to extend one of the bank edges underneath the resist bridge.

Figure 5(a) shows a mask with a large area (~800 μ^2) suspended above the substrate. For devices requiring fine structure over a larger area, it is necessary to build in supports in the mask design. The vertical and horizontal lines can be treated independently as suggested in Figs. 1(c) and 1(d). Figure 5(d) shows part of a sample made from this mask and consists of a vertical tin line which has two arrays of electrode connections on either side of the line. The joints are made to silver on the right-hand side and to tin on the left-hand side.

These examples are meant to demonstrate the feasibility of oblique deposition through offset masks for some device applications. The applications mentioned specifically in the examples are routinely carried out in our laboratory. The technique suffers from the limitations of lift-off processing in general.[1-4] Additional limitations include the presence of undesirable multiply-coated areas, the effect of shadowing by previously deposited film layers, changes in the mask dimensions during deposition, limitations on possible mask topologies, increased demand on mask quality, and the implicit requirement for directional processing techniques (e.g., vacuum deposition or ion mill erosion but not sputter or chemical etching). When applicable, however, significant reductions in attainable device dimensions are possible, and one may use a single mask to produce two or three precisely registered levels with no intermediate nonessential processing.

As a final remark, we note that it may be possible to make similar masks with electron resist. Working with basic linewidths of say 0.3 μ and a resist of comparable thickness, device dimensions of less than 0.1 μ would be accessible.

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[1] L.N. Dunkleberger (unpublished).
[2] H.I. Smith, F.J. Bachner, and N. Effremow, J. Electrochem. Soc. 118, 321 (1971).
[3] M. Hatzakes, J. Electrochem. Soc. 116, 1033 (1969).
[4] K. Grebe, I. Ames, and A. Ginsberg, J. Vac. Sci. Technol. 11, 458 (1974).
[5] J. Niemeyer, PTB-Mitt. 84, 251 (1974); see also J. Niemeyer and V. Kose, Appl. Phys. Lett. 29, 380 (1976).