Projection Photolithography-Liftoff Techniques for Production of 0.2-μm Metal Patterns

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Abstract—A technique which allows the use of projection photolithography with the photoresist liftoff process, for fabrication of submicrometer metal patterns, is described. Through-the-substrate (back-projection) exposure of the photoresist produces the undercut profiles necessary for liftoff processing. Metal lines and superconducting microbridges of 0.2-μm width have been fabricated with this technique. Experimental details and process limits are discussed.

RECENT DEVELOPMENTS in microlithography have made possible the production of a variety of devices with submicrometer (submicron) dimensions [1], [2], offering the advantages of higher speed and packing density. For many Josephson-effect devices in particular, submicron dimensions are essential for achieving optimal performance over a wide range of operating conditions [3]. For submicron pattern transfer, liftoff processing [1] generally has better resolution than wet-chemical etching. Liftoff processing may also be preferred over the alternatives of chemical and plasma etching for films which are difficult to etch, where the etching process can cause chemical or physical damage to the patterned film, or where resist masking for the etching process will lead to contamination problems for subsequent use of the patterned film.

This paper reports an optical projection technique which achieves undercut photoresist edge profiles necessary for the liftoff process [1]. With the projection technique we have developed, excellent liftoff results and yield are obtained even for dimensions <0.5 μm, and metal lines and device patterns as narrow as 0.2 μm have been produced [4]. These are as small as any patterns produced with UV-optical techniques. While electron-beam lithographic techniques [1], [2] are more general and have somewhat better resolution on solid substrates, the optical technique described here is far less complex. This simplicity and the low cost and rapid turnaround possible make this optical technique well suited for production of individual experimental devices. Other optical techniques have recently been developed which achieve undercut resist profiles suitable for liftoff processing. These are based on multiple-layer resists. These other techniques will be discussed and compared to the back-projection technique after results achieved with the back-projection technique are presented.

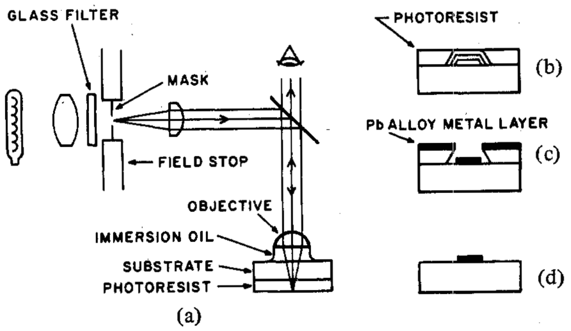

Fig. 1. Schematic diagram of back-projection and metal-liftoff procedure. (a) Exposure system, employing a Zeiss optical microscope. Image of the mask is projected *through* the substrate, which is shown in sideview. (b) Schematic contours of constant exposure intensity. (c) After photoresist development and metallization. (d) After liftoff.

The technique we have developed, through-the-substrate exposure, involves projecting the image of a mask through the *back* of a transparent substrate onto the photoresist, which is on the front side. Optical absorption in the photoresist leads to an undercut exposure profile, which is preserved after development. This exposure method is shown in Fig. 1.

The exposure system is like that of Palmer and Decker [5]. A Zeiss Photomicroscope with a type II-C epi-illuminator is used. The microscope is adjusted for Koehler illumination, with the photomask in the field stop. A 100X Oel Aufl. Pol (strain-free achromat) *NA* 1.25 oil-immersion objective is used.[1] An objective aperture of 1 mm is used for best resolution. This improves the image contrast by introducing partial coherence in the illumination. The objective aperture was chosen empirically for best visual contrast. The coherence factor with this aperture is $\sigma \approx 0.5$. With the 100X objective used, the diameter of the projected field is ~ 150 μm, and the linear reduction of the mask pattern is 43X. Non-oil-immersion achromat objectives of lower magnification and "Epiplan HD" planachromats also have yielded satisfactory results. (Resolution is best for the oil-immersion lenses, however.) The standard 15-W incandescent illuminator is used with a red-glass filter, Corning CS2-60, for focusing and alignment (see below), and with a blue-glass filter, Corning

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[1] Immersion oil is Cargille Type *A*, Cargille Laboratories, Cedar Grove, NJ 07009. The immersion oil must be removed prior to photoresist development. Removal is by wiping the oil off the surface, and then dipping in trichlorethylene one or more times.

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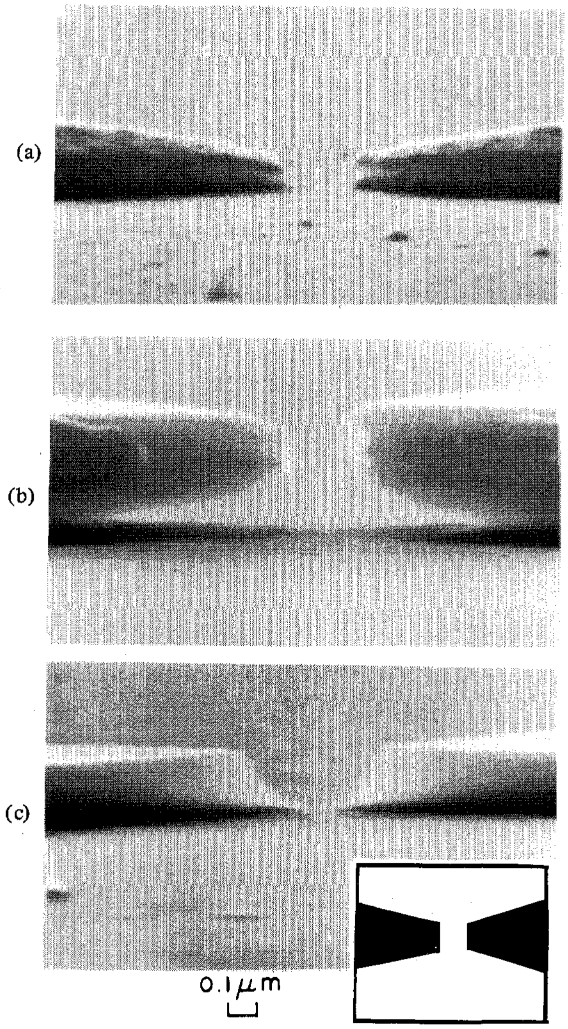

Fig. 2. Photoresist edge profiles. The scanning-electron micrographs were taken at glancing incidence (i.e., nearly parallel to the substrate). (a) Through-the-substrate exposure of thin, 0.25-μm photoresist yields roughly vertical edge profiles. (b) Through-the-substrate exposure of 0.5-μm photoresist yields clearly undercut edge profiles. (c) Conventional top-surface exposure of thin, 0.25-μm photoresist yields sloping edge profiles, which would not be suitable for liftoff processing. 0.1-μm size scale is shown. Inset: Mask pattern. The photoresist structures remain where mask is dark. The size of the gap at the center of the mask is 9 μm; this would be projected to 0.2 μm in the absence of diffraction effects.

CS5-58, for exposure. The blue exposure filter transmits at wavelengths around 400 nm. Exposure times are typically 40 s for a thin (0.3-μm) layer of the positive photoresist used, Shipley AZ1350B.[2] Standard microscope cover glasses, type No. $1\frac{1}{2}$, which are 0.17 mm thick, are used as substrates. (Most objectives designed for use with cover glasses are designed for this thickness. With oil-immersion lenses, the thickness is less critical.) The correct stage height for pattern reproduction is determined by scanning electron microscope inspection of a test series of patterns exposed at various stage heights. For the 100X lens, the correct height is within 0.5 μm of the focus point for the mask image, as viewed through the microscope.

Photoresist processing is similar to the manufacturer's recommendations.[2] The basic steps are photoresist exposure and development, metal film evaporation, and metal film liftoff (see Fig. 1). A pre-exposure bake in air at 90°C for 15 min is used; no post-exposure bake is used. Development is for 30 s in stirred AZ developer[2] diluted 1 : 1 in deionized water. If large-area patterning of the photoresist layer is required, contact exposure and development is carried out prior to projection exposure. Alignment of the microscope projection exposure to <0.5 μm is possible. Liftoff of the undesired portions of the metal film is accomplished by dissolution of the photoresist in acetone, often with ultrasonic agitation. With the resist processing procedures described, the liftoff process itself is very reliable, with a yield of >90 percent.

To achieve successful liftoff, particularly for the smaller structures, vertical or undercut photoresist edge profiles are essential. This is achieved with the back-projection technique, at least for the resist thicknesses $\geqslant 0.25$ μm used. Absorption by 0.3 μm of unexposed photoresist is ~25 percent [6], and this causes the fully exposed region to be *widest* where the light first enters the photoresist. Schematic contours of constant exposure intensity are shown in Fig. 1(b). (Interference effects are here neglected.) If the development process had infinite contrast, these intensity contours would be produced in the developed photoresist pattern. In practice, even though the development process has only moderate contrast [6], vertical or undercut edge profiles are obtained.

Electron micrographs of photoresist edge profiles for three photoresist samples, prior to metallization, are shown in Fig. 2. The inset shows the pattern projected; the gap between the resulting photoresist "fingers" is 0.3 to 0.4 μm. Fig. 2(a)-(c) are side views of each photoresist pattern, viewed at 85° from the substrate normal. In Fig. 2(a), the photoresist film is 0.25 μm thick, and shows vertical walls. Such a thickness and profile can be used for liftoff of thin metal films, <750 Å thick. In Fig. 2(b), the photoresist film is thicker, 0.5 μm thick. This profile shows dramatic undercutting, and some (unexplained) raggedness. Such a profile is typical for this thickness.[3] Finally, Fig. 2(c) shows a conventional front (top) exposure of a thin photoresist film. As expected, no undercutting results, and liftoff is unreliable with such front exposures even for thin metal films.

Diffraction effects set the lower limit on pattern dimensions. For a lens with a numerical aperture *NA*, the minimum resolvable feature has dimensions given approximately by [7], [8]

$$d_{\min} = \frac{\lambda}{2NA} \tag{1}$$

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[2] Shipley Co., Newton, MA 02162.

[3] In the discussion of resist edge profiles we have not included interference effects, which are often of importance in front exposures on reflecting substrates. As seen in Fig. 2, interference effects appear to be small. This is due to the broad-band radiation used for exposure, the smaller index mismatch between photoresist and air as compared with the case of reflecting substrates, and the large numerical aperture of the lens; see Pierre Parrens and Paul Tigreat, in *Microcircuit Engineering*, H. Ahmed and W. C. Nixon, Eds. Cambridge: Cambridge Univ. Press, 1980, pp. 181-198.

with λ the optical wavelength. Thus lenses with large numerical aperture are required for best resolution; the highest values of NA are obtained with oil-immersion lenses. Unfortunately, the depth of field, given approximately by $\Delta x = \lambda/2(NA)^2$ [7], [8] is smallest with such lenses, so that correct focusing is critical. While the ultimate resolution achieved in the photoresist pattern depends on the development conditions and the exposure-development characteristics of the particular photoresist, (1) still sets an approximate lower limit on device sizes which can be produced. Our experience shows that for isolated features, 0.2-μm linewidths are achievable with care; much smaller linewidths are rarely obtained. For dense patterns, a resolution approaching 0.2 μm may be achievable, but only with very thin resist layers.

The extremely high resolution of the combined back-exposure-liftoff technique is demonstrated by the electron micrographs in Fig. 3. Fig. 3(a) shows a 0.25-μm-wide chrome line on a glass substrate. The film is 550 Å thick. The edge roughness of $\leqslant 200$ Å is typical. Superconducting microbridge devices 0.2 and 1 μm wide are shown in Fig. 3(b) and (c). (A microbridge is a narrow constriction in a thin film; it is the thin-film analog of a point-contact structure [3].) For such two-dimensional patterns, the mask is not precisely replicated because of diffraction effects. Sharp corners of a mask pattern are rounded significantly in the photoresist pattern when photoresist pattern dimensions are $\leqslant 0.5$ μm. Grating patterns with 0.2-μm electrode width also have been produced [7] by optical-projection exposure and chemical etching. However, the edges obtained appear to be rougher than those in Fig. 3.

The procedures described here are simple and reliable and allow excellent resolution, limited only by diffraction in the high-quality microscope optics. Certain features are critical, however, and we wish to note them explicitly. First, as should be obvious, careful alignment of the microscope and objective is essential for achieving best resolution. Even with careful alignment, best resolution is obtained only in approximately the central third of the field of view. Planachromat lenses would be desirable for patterns which fill the field of view. The second point is that cover glass substrates are optimal. While patterns have been projected successfully through 0.12-mm thick sapphire substrates, the higher index of refraction of sapphire ($n = 1.8$) leads to spherical aberration. The resulting images are visibly fuzzier, and the ultimate resolution is somewhat poorer, about 0.3 μm. (Fig. 3(c) does show a quite satisfactory 1-μm microbridge pattern on a sapphire substrate.) A third important feature is that the exposure time is critical, and must be accurate to approximately ±5 percent to produce the smallest devices. Due to variations in processing, the optimum exposure time can vary up to ~ 10 percent from substrate to substrate. We therefore expose a series of devices on each substrate, over a range of exposure times. While the exposure time affects device size, clean liftoff of the undesired film is obtained for the whole range of exposure times. A final feature of note is that the use of ultrasonic agitation for liftoff requires excellent adhesion of the metal film. For chrome films this is not a problem, but for superconducting Pb-alloy films, special procedures must be employed [4].

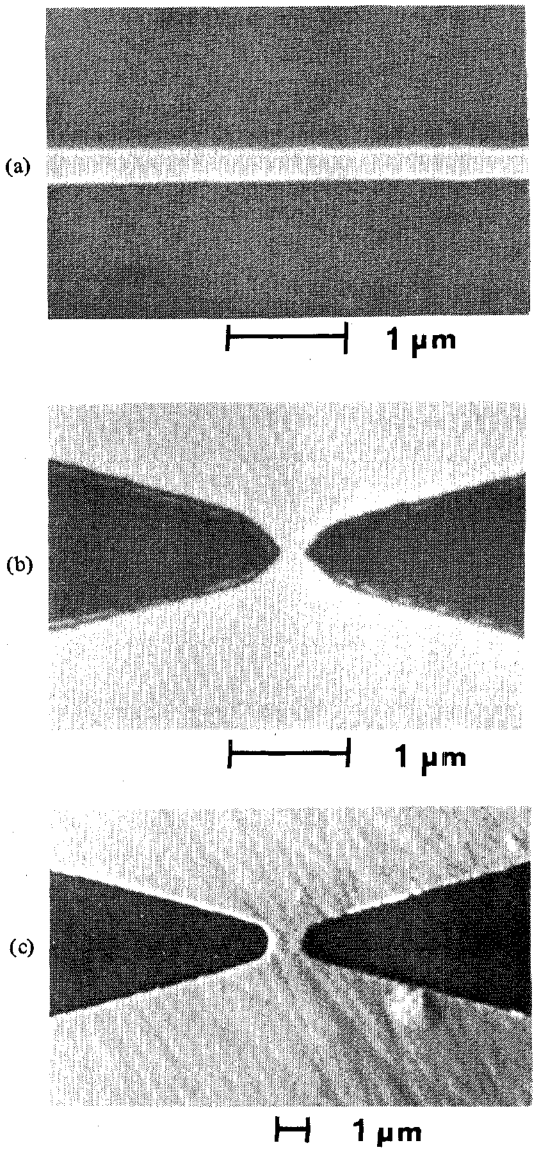

Fig. 3. Metal patterns produced with through-the-substrate exposure. Light region is the metal film; dark region is the substrate. Viewed with SEM at normal incidence. (a) Chrome line, 0.25 μm wide, on a cover-glass substrate; 550-Å film thickness; (b) Pb-In alloy microbridge, 0.2 μm wide, on a cover-glass substrate; 250-Å film thickness. In (a) and (b), the photoresist was exposed with 100×, oil-immersion lens. (c) Pb-alloy microbridge, 1 μm wide, on a sapphire substrate; $\sim$500-Å film thickness. Polishing marks in this sapphire substrate are visible. The photoresist was exposed with a 40× lens. In (b), the hazy lumps within $\sim$700 Å of the main film (the bright region) are due to migration or scattering under the overhanging photoresist (Fig. 1(c)) of a thin (50-Å) Pb-oxide undercoat layer, deposited and oxidized at room temperature to promote adhesion of the 250-Å thick Pb-alloy film. The Pb-alloy film was then deposited at 77 K to avoid migration and reduce grain size. The masks used for producing the devices of Fig. 3(b) and (c) had the shape of the metal pattern of Fig. 3(c).

The back-projection technique described in this paper serves a specific set of processing requirements: the use of thin, transparent substrates, with single-layer metallization. These requirements apply for certain Josephson devices and electrontransport experiments. On thick or opaque substrates, undercut photoresist profiles may be produced with other, complementary techniques, such as multilayer resists [9][4] or chemical treatment of the top layer of the photoresist to slow development [10]. Also, for a limited number of simple structures, even smaller linewidths, $\leqslant 300$ Å, are possible if pattern *edges* can be used to define feature dimensions [11]. The back-projection technique is, however, ideally suited for the production of flexible submicron masks for conformal replication [1]. Thus the metal patterns produced with the back-projection technique may be utilized as masks in a much wider variety of applications.

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[4] In addition to the techniques described in [9], a number of other multilayer resist techniques for near UV-optical exposure have been developed; see, for example, Bruning [8]. However, these other techniques require either a vapor-deposited resist or plasma etching to etch through an intermediate layer, and are thus more complex than those of [9].

Multilevel Resist for Lithography Below 100 nm

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Abstract—**Features as small as 25 nm have been made with electron-beam lithography using multilevel resists on thick silicon substrates. Liftoff patterning of metal lines and reactive ion etching of silicon have demonstrated the possibility of making device structures with lateral dimensions below 100 nm.**

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I. INTRODUCTION

FURTHER INCREASE in complexity of integrated circuits depends in large part on continuing improvement in the lithographic patterning process. Techniques having higher resolution than optical exposure, such as e-beam or X-ray lithography, do not necessarily yield finer patterns. Each component of the patterning process is important in achieving high