Fabrication of 300-Å metal lines with substrate-step techniques

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Metal lines as narrow as 300 Å and as long as 0.5 mm have been fabricated by new techniques based on substrates with surface-relief steps. Substrate steps with a square profile are formed by ion-beam etching. Metal wires of triangular cross section are produced by ion-etching a metal-coated substrate at an angle, so that the wire is formed in the shadow of the step. An alternative process, direct evaporation onto the step edge, is used to produce lines of very high aspect ratio of height to width.

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Recently a number of investigators have reported techniques which allow production of individual metal lines of width $<0.2\,\mu$m (200 nm).[1-5] The narrowest lines have been produced with electron-beam lithography and ion etching. On thin (60 nm) substrates, negative resist patterns of PMMA (polymethylmethacrylate) have been exposed to produce metal lines of 15 nm linewidth.[1] Contamination resist patterns have been used to produce 8-nm metal lines on 10-nm-thick carbon substrates.[2] These experiments used a complex exposure system based on a scanning transmission electron microscope for optimal control. Thin or window substrates were necessary to avoid electron backscattering. Other methods employing advanced exposure techniques have recently been developed to produce narrow lines on *thick* substrates. Two-layer electron resist structures, which reduce electron backscattering effects in the upper layer, have been employed[3] for production of 35-nm gold lines on thick silicon substrates by electron exposure and resist liftoff. The finest metal lines on thick substrates, 20-nm-wide tungsten lines,[4] have been produced by x-ray lithography and liftoff techniques. The high-aspect-ratio tungsten absorber masks were fabricated by a shadow-evaporation technique.

Direct application of photolithography and shadow-deposition techniques[5,6] to produce fine lines have used pattern edges in photoresist, and have been limited to widths $\geqslant 150$ nm. The narrowest lines reported[5] display edge roughness and width variation of ≈ 50 nm.

We report here photolithographic-ion-milling techniqes for producing, on thick substrates, uniform-width metal lines at least as narrow as 30 nm, comparable to lines produced with the advanced exposure techniques. Studies of "one-dimensional" electron transport and localization in fine metal wires as narrow as 40 nm have recently been carried out[7] using wires produced with one of the techniques to be described. Ultrasmall Josephson microbridge devices have been produced by a two-dimensional extension of these methods.[8] In this letter we present, for the first time, the specific process information, fabrication results, and size limits for production of the fine metal wires.

The two procedures used to form a fine metal wire, denoted Processes A and B, are shown in Fig. 1. We use $Au_{60}Pd_{40}$ metal as an example of a fine-grain soft alloy. (It is referred to below as Au-Pd.) Process A comprises steps a–e. Process B consists of steps a–c and f:

a. Half the substrate is coated with a thin chrome film, using photoresist-liftoff techniques.[9,10] Both conformal[9] and through-the-substrate projection[10] exposure provide the required undercut profile in the AZ-1350B resist. Substrates are standard Corning type 0211 microscope cover glasses, individually wrapped.

b. The substrate is ion etched at normal incidence to produce a square step in the substrate. An unneutralized 5-keV argon-ion beam is used. An oxygen partial pressure of 2×10^{-5} Torr significantly reduces the etching rate of the chrome film, R_{Cr}, relative to that of the glass.[11,12] Alternatively, a reactive-ion etching beam using CF_4 etch gas achieves an enhanced etch rate of the glass substrate.[8]

c. The chrome film is removed in a chemical etch of ceric ammonium nitrate, nitric acid, and water.

d. For process A, a Au-Pd film is sputtered, or evaporated at an angle, so that the edge of the step is fully coated. The coated substrate is then ion etched in an argon-ion beam

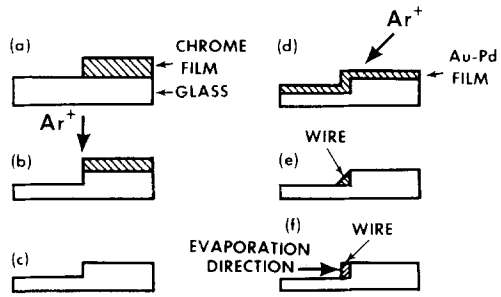

FIG. 1. Fabrication procedures for production of fine metal wires. The substrate is a microscope cover glass, shown in side view. Procedures a–c are the same for both process A and process B. a. Half the substrate is coated with a thin chrome film. b. The substrate is ion etched to produce a square step. c. The chrome film is removed with a chemical etch. Process A: d. The substrate is coated with the metal film (e.g., Au-Pd), and ion etched at an angle until e. A nearly triangular wire is formed along the step edge. Process B: f. The metal film is evaporated parallel to the substrate to coat only the step edge. A subsequent ion etching normal to the substrate may be required to remove the light coating on the rest of the substrate.

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at an angle such that the step shadows the Au-Pd film on its edge. Etching is continued until all the Au-Pd film, except that protected by the step edge, is removed. For this etching procedure, ion energies $\leqslant 0.5$ keV are used. This was found necessary to avoid removal of the metal film on the step edge. Ion penetration may play a role in this Au-Pd film removal at high ion energies (~ 5 keV). In addition, at high ion energies and currents significant heating occurs and the wire may peel off sections of the step edge. The etch rate of Au-Pd at low ion energies and currents[13] is < 1 nm/min; the inferred ion current is $< 10\,\mu A/cm^2$.

e. An exactly triangular profile would result above if the etch rate of the glass were zero for step d. For Au-Pd and glass, the measured ratio of etch rates is 3:1, so the cross-sectional profile of the wire is nearly triangular once etching is completed, but the substrate is also partly etched.[14]

f. In process B, the wire is evaporated directly on the edge of the step. This process is similar to that used by Flanders[4] to produce high-aspect-ratio x-ray masks. In this evaporation, the rest of the substrate is lightly coated as well. It may be cleaned with a brief ion etching at normal incidence if the light coating is electrically continuous.

Wires as narrow as 30 nm have been formed with both process A and process B, and scanning electron micrographs of typical wires are shown in Fig. 2. A Au-Pd wire 0.3 μm (300 nm) wide, formed by process A, is shown in Fig. 2(a). This wire is not quite fully etched to the triangular shape. The roughness visible is due to the relatively thick chrome masking film required to produce the large substrate step. In Fig. 2(b), a triangular $Pb_{90}In_{10}$ wire 0.2 μm wide is shown. Even though the wire has been fully etched, small spots of the metal film remain on the substrate owing to the very nonuniform milling of these Pb alloys.

Figure 2(c) shows a rectangular Au-Pd wire, formed by process B. This wire is 30 nm wide. The step height is 50 nm. The very straight edge and uniform cross section seen here are typical of the wires obtained. Figure 2(d) shows a similar wire, but at a lower magnification. Based on observed grain sizes of thin Au-Pd films,[2] much finer wires with widths as small as 10 nm should be possible. Transmission electron microscopy is required to establish wire quality for this size scale.[1,4]

With the processing methods outlined, the yield of uniform and continuous wires is high. This is largely due to the excellent uniformity of the ion-milling process and its application in a fully self-aligning procedure. Numerous electrically continuous wires 100–450 μm long have been formed, with electrical resistances as expected from the bulk resistivity and the measured step height and length. Maximum wire length was set by the field of view of our projection photolithography system. Since the processes are self-aligning, the wire forms readily even around long-scale wiggles in the step edge (as viewed from above). Gross mask or process defects can still prevent wire formation, but these are readily detected with an optical microscope.

The fine-scale raggedness of the shallow steps presently sets the lower limit on wire size. This raggedness is 10–20 nm, and results from the edge roughness of the chrome mask. Finer-grain masking films like Ni-Cr are found to yield smoother edges, but have a larger ion-etching rate. The step profile itself is square and sharp to better than 20 nm, and is not at present a limiting factor. Optical diffraction effects do not preclude the fabrication of finer wires, since *height* dimensions are used to define feature dimensions. Such height dimensions can be measured and controlled to an accuracy of better than 10 nm with conventional techniques.

The procedures described offer a number of advantages for laboratory and individual device studies. Both processes are simple, can use thick substrates, and may be employed with a variety of materials. (Process A is suitable only for soft metals or those that can be etched with reactive gases.)

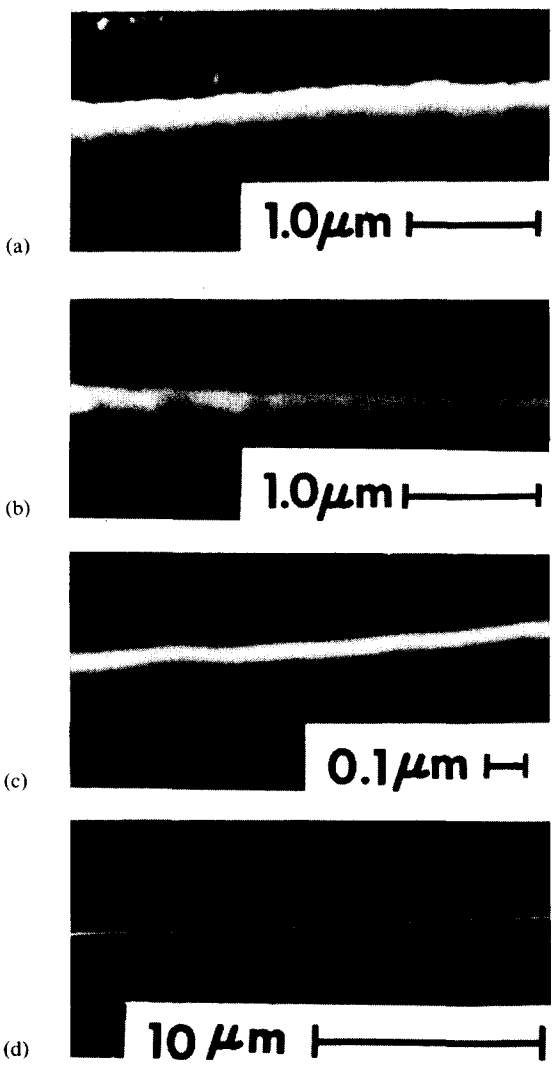

FIG. 2. Scanning electron micrographs of fine wires. Process A: a. Wire of $Au_{60}Pd_{40}$, 0.3 μm wide, not fully etched. The resulting cross section is not quite triangular. b. $Pb_{90}In_{10}$ wire, 0.2 μm wide, of triangular cross section. Spots of metal remaining are due to nonuniform etching of this Pb alloy. This nonuniform etching also leads to some width variation. Process B: c. Narrow wire of $Au_{60}Pd_{40}$, approximately 30 nm wide, on a step edge 50 nm high. d. Wire similar to that in Fig. 2(c), at lower magnification. In Figs. 2(c) and 2(d) note the excellent uniformity and straightness of the wire. {Roughness evident in Figs. 2(a) and 2(b) is due to edge roughness of the *thick* chrome mask film required to produce the deep substrate step [Fig. 1(b)].} Wires as narrow as 30 nm have also been produced with Process A. High part of the substrate is at the top of each micrograph.

Wires can be relatively long, $\approx \frac{1}{2}$ mm, and electrical contact is easily established. While the techniques described cannot produce high density or complex patterns, they are ideally suited to production of individual conducting wires for studies of one-dimensional effects in superconducting, magnetic, or normal metals, and in Josephson devices. As compared with previous photoresist-shadowing-liftoff techniques,[5] the ion-etching process offers much better edge definition and height control, and thus much narrower and more uniform wires. Also, the metal wire itself is not exposed to any chemical etchants during processing. Finally, unlike organic resist liftoff processes, the techniques reported here allow the substrate to be heated during film deposition, as may be required in the production of high-T_c refractory superconducting films.[15]

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[12]The measured ratio of etching rates $R_{glass}:R_{Cr}$ is 2.5:1 for an argon-ion beam in an oxygen pressure of 2×10^{-5} T; the typical etching rate of the 0211 glass is 5 nm/min. for an ion-beam energy of 5 keV. To etch a 50-nm step in the substrate, a chrome film 40 nm thick is used. The thickness of the chrome film represents a compromise between minimizing the effects of mask faceting, which favors a thick film, and obtaining good edge definition, which favors a thin film. See M. Cantagrel, IEEE Trans. Electron. Devices **ED-22**, 483 (1975).
[13]Ion source used is a cold-cathode source, Commonwealth Scientific Model 2-30. To obtain low ion energies (< 1 keV), the polarity of the accelerator power supply is reversed.
[14]In many applications the exact cross-sectional profile of the wire is unimportant and only the area of the wire must be known precisely; for the Au-Pd wires studies in Ref. 7, process A was employed and the exact area was determined from the measured electrical resistance.
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Internal photoemission in hydrogenated amorphous-Si films

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Measurements of internal photoemission from metal contacts into amorphous SiH_x are reported. The height of the barriers at Cr, Pd, and Pt contacts were found to be 0.83, 0.98, and 1.12 eV, respectively, from the photoemission threshold.

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Internal photoemission is a widely used technique for studying the electronic properties of metal-semiconductor junctions.[1] In this letter, we report the first observations of internal photoemission from metal contacts into hydrogenated amorphous silicon (a-SiH_x) films and the first direct measurements of the Cr, Pd, and Pt/a-SiH_x Schottky barrier heights. In order for photoemission to be observable, the semiconductor must have a low optical absorption below the energy gap. Otherwise the photocurrent due to carriers generated in the semiconductor (process A in Fig. 1) will overwhelm the photoemission current (process B in Fig. 1). We have found that undoped a-SiH_x films prepared under conditions that give good photovoltaic properties also exhibit steeply decreasing exponential absorption tails[2] below the band-gap energy and consequently have readily observable internal photoemission.

The a-SiH_x films were deposited in a 13-MHz capacitive plasma reactor at a power density of 0.3–0.5 W/cm^2. A flow rate of 5–20 scc/min of CCD-grade silane and a pressure of 30 mTorr were maintained in the reactor. The substrates were held at 240 °C on the anode, which was grounded electrically. Under these deposition conditions, the films contained about 16 at. % H, primarily in the monohydride[3] bonding configuration. More details of the preparation method will be published elsewhere.[4] Schottky barrier solar cell structures[5] were fabricated on 7059 glass coated with conductive indium tin oxide and 50 Å of Cr. A 500-Å layer of n^+a-SiH_x was deposited on top of the Cr from a silane discharge containing 2% PH_3. This layer formed a good ohmic contact with a 3–5-μ layer of undoped material deposited immediately afterward. Semitransparent Cr, Pd, and Pt contacts, 100 Å thick and 2 mm^2 in area were evaporated on

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