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The focused ion beam as an integrated circuit restructuring tool

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One of the capabilities of focused ion beam systems is ion milling. The purpose of this work is to explore this capability as a tool for integrated circuit restructuring. Methods for cutting and joining conductors are needed. Two methods for joining conductors are demonstrated. The first consists of spinning nitrocellulose (a self-developing resist) on the circuit, ion exposing an area, say, $7 \times 7\,\mu$m, then milling a smaller via with sloping sidewalls through the first metal layer down to the second, e-beam evaporating metal, and then dissolving the nitrocellulose to achieve liftoff. The resistance of these links between two metal levels varied from 1 to 7 Ω. The second, simpler method consists of milling a via with vertical sidewalls down to the lower metal layer, then reducing the milling scan to a smaller area in the center of this via, thereby redepositing the metal from the lower layer on the vertical sidewall. The short circuit thus achieved varied from 0.4 to 1.5 Ω for vias of dimensions $3 \times 3\,\mu$m to $1 \times 1\,\mu$m, respectively. The time to mill a $1 \times 1\,\mu$m via with a 68 keV Ga^+ beam, of 220 Pa current is 60 s. In a system optimized for this application, this milling time is expected to be reduced by a factor of at least 100. In addition, cuts have been made in 1-μm-thick Al films covered by 0.65 μm of SiO_2. These cuts have resistances in excess of 20 MΩ. This method of circuit restructuring can work at dimensions a factor of 10 smaller than laser zapping and requires no special sites to be fabricated.

I. INTRODUCTION

The ability to reconfigure the conductors in an integrated circuit after it has been fabricated has a number of practical applications, such as defect avoidance, circuit customization, circuit testing, failure analysis, and permanent memory programming. A wafer-scale digital integrator has been reported in which the removal of defective circuit blocks and the "wiring in" of redundant blocks plays a central role.[1] A laser is used to cut conductors and to fuse prefabricated link sites, thereby joining conductors. In the fabrication of large random access memories laser cutting of conductors is widely used to replace defective lines.[2]

Several techniques have been developed or explored for use in circuit restructuring. For the laser linking of conductors special sites have been fabricated[1] consisting of sandwiches of Al, SiO_2, amorphous Si, SiO_2, and Al, which can be reliably laser fused to produce a desired short circuit. Laser microchemical etching and deposition have been reported.[3] For removal of Al a liquid etchant covers the surface and etching occurs under the laser spot. For the addition of poly-Si conductors the circuit is placed in an ambient of 200 Torr of diborane-doped silane gas. The e-beam charging of gates has also been demonstrated as a technique for restructuring integrated circuits or programming EPROM's (erasable programmable read only memory).[4] None of these techniques is ideal in every way. Extra fabrication steps, wet chemistry, large area, or relatively high resistance links are some of the drawbacks.

The purpose of this work is to explore the focused ion beam as a high resolution tool for circuit restructuring or for other kinds of circuit microsurgery.

II. EXPERIMENTAL

A two-level metal structure shown in Fig. 1 was fabricated from existing masks. At the intersection points, which have dimensions $10 \times 8\,\mu$m, the two levels of Al are separated by 0.65 μm SiO_2. One of our goals is to create a short circuit between these two levels.

A Ga^+ focused ion beam was used with energy between 50 and 70 KeV and beam current between 100 and 300 pA. Beam diameters were from 0.1 to 0.7 μm. Electrons emitted by the ion impact were detected with a channel electron multiplier to form an image on the CRT. Either the single lens column at Hughes Research Laboratories or the Microfocus™, a three-lens column with an $E \times B$ mass separator, at Ion Beam Technologies was used.

After ion beam fabrication a probe station was used to test the result. Four probes were placed on the four pads surrounding a given crossing point (Fig. 1). By measuring all possible combinations of resistances and averaging appropriately, the resistance of the link was measured, and contact and conductor resistance was eliminated.

III. RESULTS

Two schemes were considered for joining crossing conductors on two levels. They are shown in Figs. 2(a) and 2(b).

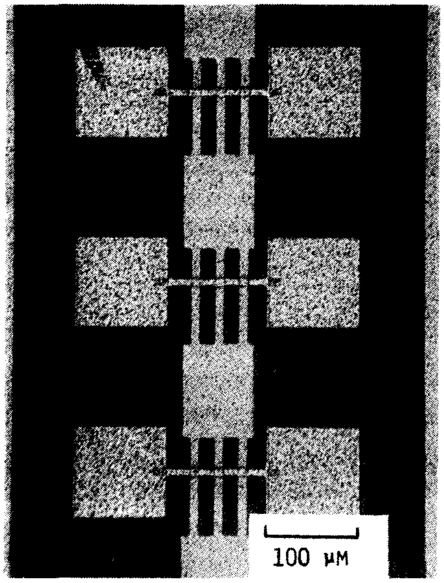

FIG. 1. Pattern of Al conductors on two levels used to test the restructuring. The horizontal conductors are 8 μm wide, and the vertical three parallel conductors, which are on top, are 10 μm wide. Links are made in the $8 \times 10\ \mu$m intersection area.

The first combines a number of techniques: nitrocellulose, a self-developing resist,[5] is spun on the wafer; the ion beam is used to develop out a small area of the nitrocellulose; then, in the middle of this area, the ion beam is used to mill a sloped sidewall via which penetrates the top layer of metal and the oxide, and extends to the lower level of metal; Al is e-beam evaporated and liftoff is performed leaving a metal plug which shorts the two layers together. In the second scheme, redeposition is used. A via with vertical sidewalls is milled to the lower level, then milling is continued over a reduced area so that metal redeposits on the vertical sidewall creating a short circuit.

Although the second scheme is preferable because of its simplicity, we will also present our results on the first scheme. This scheme, with modifications, may have other uses, for example, to connect two buried layers in different parts of an integrated circuit by milling vias and putting in a bridge by liftoff.

A. Nitrocellulose with evaporation

Because nitrocellulose self-develops with ion bombardment,[5] via milling and resist, exposure/development are combined in one step. (The material removal rate due to self development is about three orders of magnitude faster than by milling.) The use of conventional resist would require aligned optical exposure and ion exposure, as well as wet development. However, to use the nitrocellulose scheme two questions must be answered; (i) is the circuit visible in the scanning ion microscope mode when it is covered by the resist, and (ii) does ion beam exposed nitrocellulose have vertical sidewalls suitable for liftoff? Fortunately, a circuit such as in Fig. 1 covered by 2 μm of nitrocellulose can be seen in the scanning ion microscope mode with a resolution of about 1 μm. In 10 s, the time needed to take a photo or to align the desired spot in the center of the screen, the dose to a

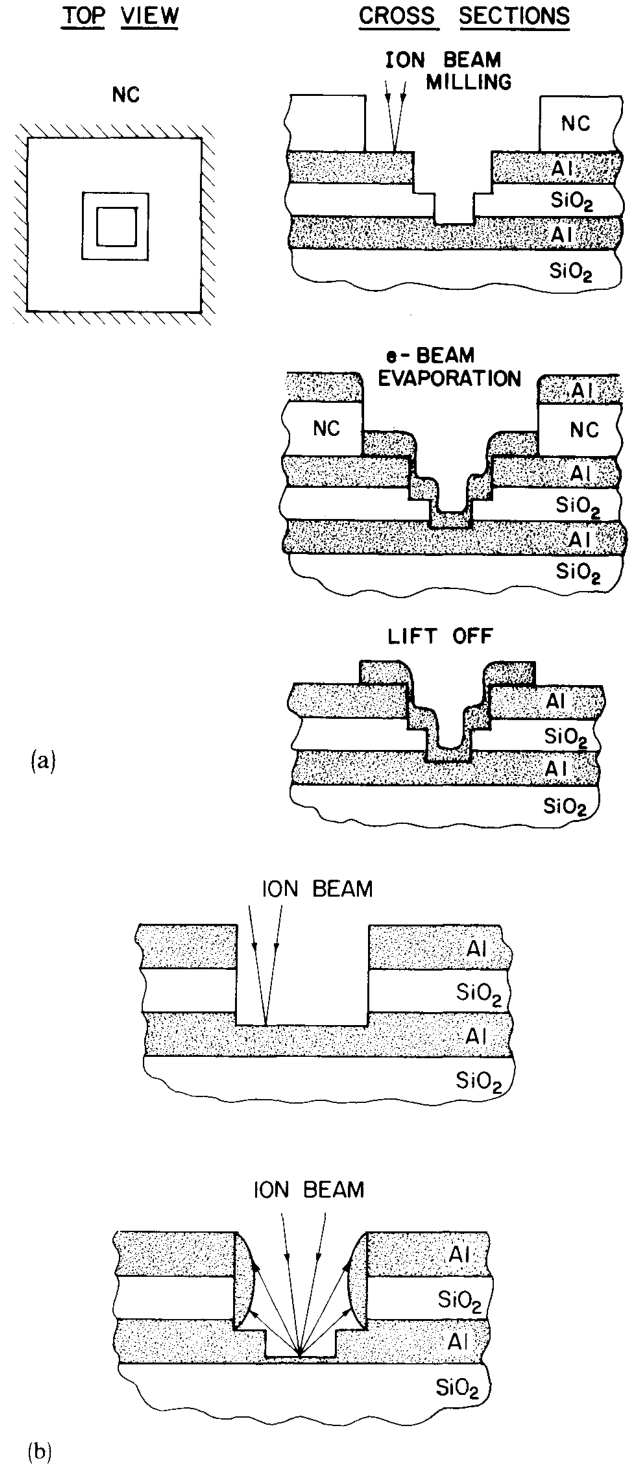

FIG. 2. (a) Schematic of the joining of conductors using a film of nitrocellulose spin of the wafer exposed (and developed simultaneously) by the ion bean, via milling, metal evaporation, and liftoff. (b) The joining of conductors using ion redeposition of the lower layer of metal.

$100 \times 100\ \mu$m area is 1.6×10^{14} ions/cm^2. This is only 3% of the dose needed for complete nitrocellulose exposure. To answer the second question, ion beam exposed nitrocellulose films are shown in Fig. 3. Clearly vertical sidewalls are observed. An undercut profile can be obtained by adding a thin film of polymethylmethacrylate (PMMA) over the nitrocel-

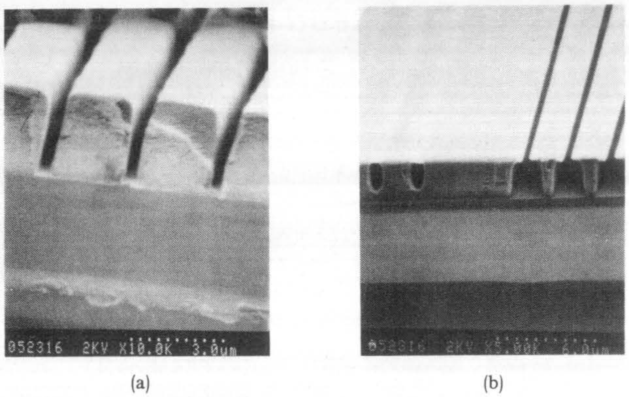

FIG. 3 (a) Nitrocellulose (NC) exposure and simultaneous development using focused ion beam. On left NC 2-μm-thick exposed to 6×10^{15} ions/cm^2 in a single pass of the Ga^+ ion beam (65 kV, beam diameter 0.1 to 0.15 μm). Note the vertical sidewalls and the 0.4 μm linewidth. (b) NC covered with 0.15 μm of PMMA. Dose on left is 1.2×10^{16} ions/cm^2. Note that on the left the NC is developing out even before the PMMA is milled through. The structure on the right, written with a dose of 1.2×10^{17} ions/cm^2, is ideal for liftoff.

lulose, as seen on the right side of Fig. 3.

An example of nitrocellulose exposure and via milling is shown in Fig. 4. The 7×7 μm opening in the nitrocellulose was milled first, then the 1×1 μm, followed by the 1.5×1.5 μm via. The reason for milling the smaller one first is to round off the step at the top of the 1×1 via and to avoid unwanted redeposition of SiO_2. After Al evaporation liftoff was performed in acetone with ultrasonic agitation. Optimally fabricated vias showed resistances between levels of 1 to 7 Ω. We suspect the variation is due to the fact that the sample was exposed to air after ion milling and not annealed after e-beam evaporation.

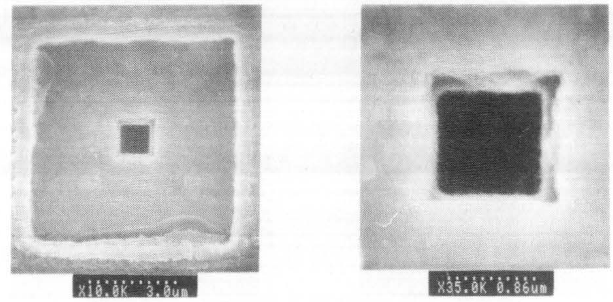

FIG. 4. 7×7 μm opening on the left in the nitrocellulose 2-μm-thick, the dose was 1.5×10^{16} ions/cm^2. The small central via was milled 1×1 μm with a dose 2.1×10^{18} ions/cm^2 followed by 1.5×1.5 μm at a dose of 1.5×10^{18} ions/cm^2. All doses at 65 kV Ga^+ with 220 pA beam current. Beam diameter 0.1 to 0.15 μm. Sample covered by 0.2-μm-Al, before liftoff. The smooth fluid-like protrusion at the edge of the via is due to electron exposure of the NC in the SEM.

B. End-point detection

If, during the milling of a via, we monitor either the current from sample to ground or the electron emission, as seen on the display, we get a clear indication of the level being milled. This is shown in Fig. 5. While the Al film is milled the electron emission is high, the current is high, and the display is bright. As the milling breaks through to the oxide the current drops, and the display darkens. As seen in the display this breakthrough does not occur uniformly everywhere at once because the initial Al film is rough. When the second deeper SiO_2 film is reached, the drop in current is not as high because the 2.3-μm-high edges of the pit emit electrons strongly. This again is seen in the display as bright thick edges.

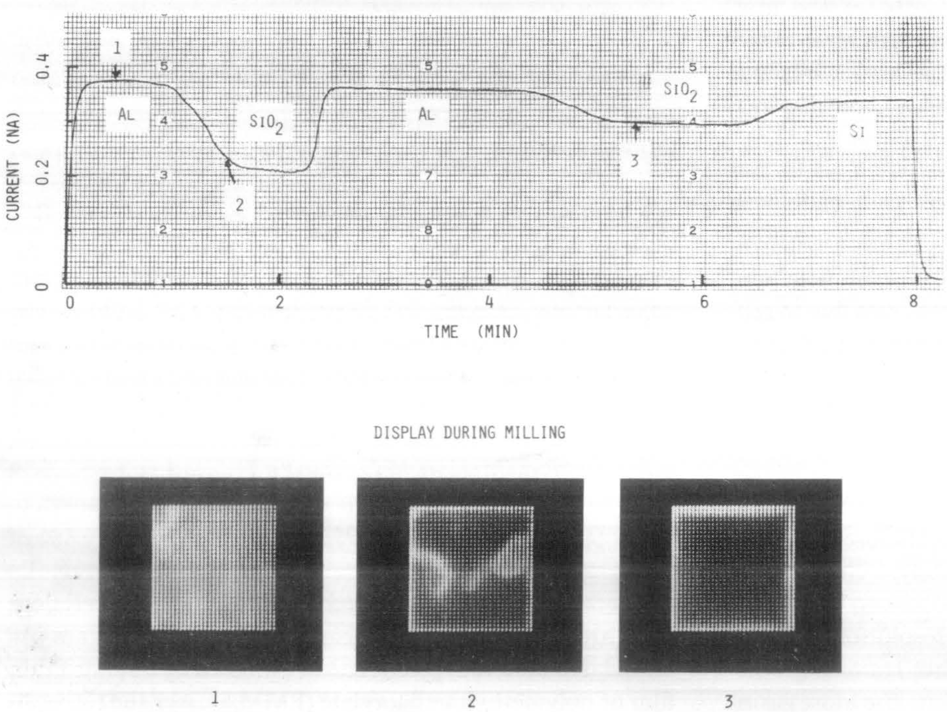

FIG. 5. "End-point" detection by monitoring sample current. The current is the sum of incident ion current and emitted electron (or ion) current. The emitted current is different for SiO_2 and Al causing a variation as a function of milling time or via depth. The via is 3×3 μm. The lower part of the figure shows the display at three points (labeled on the curve) during the milling. The beam is stepped in 0.1 μm steps, and the display is 30×30 pixels.

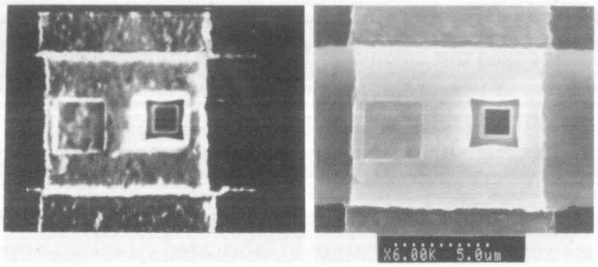

FIG. 6. Top view of milled via with redeposition. On left, scanning ion micrograph; on right, scanning electron micrograph. Resistance between levels is 0.4 Ω.

The end-point detection scheme works similarly for vias 1.5×1.5 μm, but for vias 1× 1 μm no modulation in the current or electron emission can be seen.

By reading off the times taken to mill through the various layers from Fig. 5 we can calculate the yield of atoms or molecules sputtered per incident ion. With a beam current of 220 pA at 68 kV Ga^+ we get a yield of 3.6 atoms/ion for the first Al layer and 2.4 atoms/ion for the second. In another measurement on a more open Al film we obtained a yield of 4.2 atoms/ion. This trend of slower milling for deeper pits is in qualitative agreement with earlier measurements.[6] For SiO_2 we measured a yield of 2 molecules/ion for an open structure and 1.2 molecules/ion for both of the SiO_2 films of our sample. The fact that both films mill at the same rate is surprising since one would expect the deeper film to mill more slowly.

C. Links by redeposition

The redeposition scheme illustrated in Fig. 2(b) was tested with via pairs of several dimensions; 3×3 μm followed by 1.5×1.5 μm, 1.5×1.5 μm followed by 1×1 μm, and 1×1 μm followed by 0.5×0.5 μm. The results for the largest via are seen in Fig. 6 which shows the identical structure viewed in a scanning electron microscope (SEM) or a scanning ion microscope (SIM). The SEM, of course, has higher resolution, but the SIM is more sensitive to topography. As seen in Fig. 6, at each site a shallow via nominally 3×3 μm was first milled on the left to establish its dimensions. Then, by comparing its width with the deep via on the right we can measure approximately the thickness of redeposition to be 0.3 μm in the center of each edge.

Vias of these dimensions connected the top and bottom films of Al with a resistance of 0.4 Ω. Vias of 1.5×1.5 μm followed by 1×1 μm also had 0.4 Ω resistance. The smaller vias, 1×1 μm followed by 0.5×0.5 μm, had 1.3 to 1.5 Ω resistance. Figure 7 shows a via 1×1 μm with redeposition. (In a normal incidence view the bottom of the via cannot be seen, indicating that in the SEM, as well as the SIM end-point detection above, the electrons cannot get out.) We have also observed that a hole of approximate diameter of 0.2 μm milled by a stationary beam in some cases resulted in a 30 Ω connection. We do not as yet understand the mechanism for the conduction. The advantage of this small via is that it can be milled in a few seconds, whereas the larger vias above require 1–4 min.

D. Cuts in conductors

The focused ion beam can be used to simply mill away part of a conductor to create a desired open circuit. We have made cuts varying in width from 0.1 to 1.2 μm. The very smallest cut showed an open circuit of 100 kΩ but then broke down at 0.5 V to produce a short. A SEM examination showed balls of material, presumably Al, bridging the opening. The larger cuts always had resistances in excess of 20 MΩ (the limit of our meter). In one case an electrometer was used and 10^9 Ω measured. A cut is shown in Fig. 8. Our results are summarized in Table I.

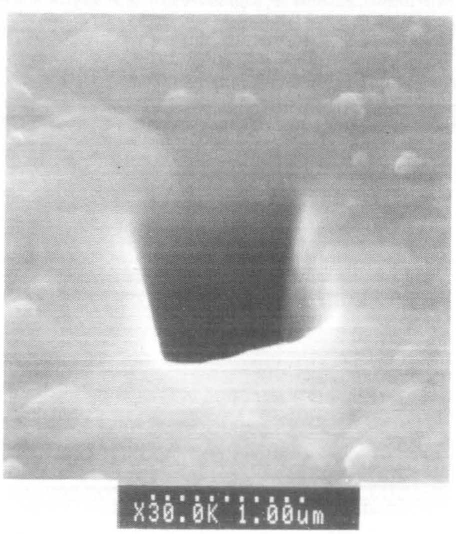

FIG. 7. Inclined view of a 1×1 μm via with redeposition. Resistance is measured to be 1.5 Ω.

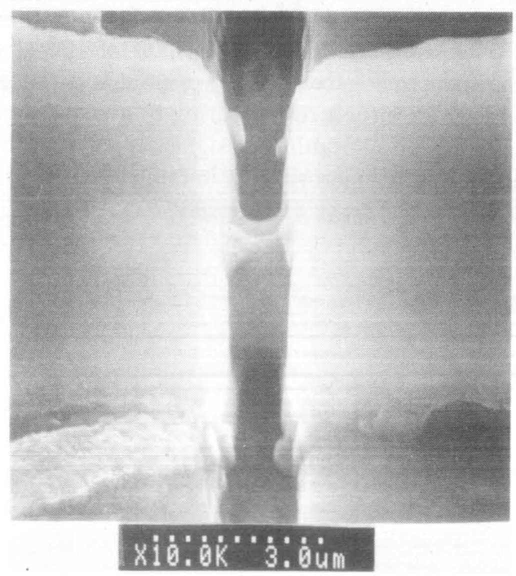

FIG. 8. Scanning electron micrograph of an ion milled cut made in a conductor, 1-μm-thick Al, covered by 0.6 μm of SiO_2, resistance greater than 20 MΩ.

TABLE I. Summary of results.

Links	Dimensions (μm)	Time (s)	Resistance (Ω)
Nitrocellulose (NC) and evaporation	7×7 patch 1.5×1.5 via	37	1–7
Redeposition	3×3 via 1.5×1.5 red.	230	0.4
	1.5×1.5 1×1	86	0.4
	1×1 0.5×0.5	62	1.3
Redeposition (?)	0.2 diam	4	30
Cuts	10×1.2×1.5	900	>20 M
	10×0.7×1.5	450	>20 M
	10×0.1×1.5	180	100 K

IV. DISCUSSION

The above results indicate that the focused ion beam is a potential circuit restructuring tool, particularly if a limited number of interventions are needed. It possesses several advantages compared to other techniques such as laser zapping, laser deposition or etching, and e-beam charging of gates: (a) both links and cuts as well as imaging are done with the same instrument, (b) resistance of links is low, (c) no special fabrication is needed, i.e., any crossing conductors can be connected.

The milling times quoted in Table I do not fairly represent the capabilities of this technique. In most cases, a larger beam diameter is expected to work as well as 0.1–0.15 μm. Tripling the diameter decreases the time by about an order of magnitude, since the current density remains constant. In addition, a machine with a current density of 10 A/cm^2, compared to our 1 A/cm^2, has been reported.[7] With increased current density and larger beam diameter the intervention time will be reduced by a factor of 100 or more. Thus, the focused ion beam is a versatile and potentially practical tool for circuit restructuring to avoid defects, for circuit customization or minor design changes after fabrication, and for circuit microsurgery in failure analysis.

V. SUMMARY

The focused ion beam is able to make micron and submicron links in two crossing conductors in an integrated circuit. It can also make cuts of submicron dimensions in conductors buried under SiO_2. No special sites need to be fabricated. These features make it a candidate for circuit restructuring. In addition, the focused ion beam can be used to make minor design charges in fabricated circuits, to open or make contacts for circuit testing, to alter circuits for failure analysis, and in other situations where few interventions are needed. Thus it is a powerful tool for integrated circuit microsurgery.

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