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To cite this version:

P. Prewett. FOCUSED ION BEAMS IN MICROFABRICATION. Journal de Physique Colloques, 1989, 50 (C8), pp.C8-179-C8-190. <10.1051/jphyscol:1989832>. <jpa-00229930>

HAL Id: jpa-00229930
https://hal.archives-ouvertes.fr/jpa-00229930

Submitted on 1 Jan 1989

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FOCUSED ION BEAMS IN MICROFABRICATION

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Abstract - Focused ion beams, generated from high intensity liquid metal field emission ion sources, can be used both for machining and deposition. Their potential applications in microfabrication of semiconductor microcircuits range from mask and integrated circuit repair to lithography and direct write ion implantation doping.

1 - INTRODUCTION

It is now more than ten years since the earliest use of liquid metal field emission ion sources (LMIS) to produce high intensity submicron focused ion beams /1/. Since then, there has been a considerable growth in the field, with focused ion beam (FIB) systems being developed for use in surface analysis and microfabrication.

It was originally thought that the patterning of resist layers by ion beam lithography (FIBL) might ultimately supplant electron beam lithography for the manufacture of microcircuits having densely packed submicron features /2,3/. Though this now seems unlikely, interest in FIBL is still strong for a number of special applications. In addition, the use of focused ion beam implantation (FIBI) for direct doping of microcircuit features has been made possible by the development of alloy LMIS and focusing columns incorporating ion mass-to-charge filters /4/.

While FIB systems for FIBL and FIBI are becoming increasingly sophisticated, the largest growth of interest during recent years has been in systems for perhaps the simplest FIB process of all, viz. micromachining by ion sputtering (FIBM). Systems combining FIBM and focused ion beam deposition (FIBD) are increasingly used for repair of masks used in microcircuit fabrication and for the repair of part processed and finished microcircuits and several commercial systems are now available. In addition to microfabrication for integrated circuit technology, the range of potential applications for FIB technology is growing rapidly to include machining of low dimensional structures for fundamental studies in GaAs and an increasingly wide range of applications extending beyond the field of microelectronics.

2 - FIB EQUIPMENT

Most of the ion optical systems used in focusing of beams from LMIS have performance which is dominated by chromatic aberration, associated with the energy spread of ions emitted from the liquid protrusion at the apex of the source. It is currently believed that this may have dimensions as small as a few tens of nm, supporting emission currents typically up to ~5μA in subμm focused beam applications. The energy spread is thought to be a consequence of Coulomb interactions of ions in the very intense beam near the liquid emitter /5,6/. For the simple case of a single focusing lens for which all acceleration of the beam occurs before focusing, the current density available in the final ion probe can be shown to be /7/

\[ J = 4N^2\frac{V}{C^2} \Phi \]

(1)

for a lens of magnification \( M \) and final beam energy \( eV \) for singly charged ions. \( C \) is the chromatic aberration coefficient of the lens, referred to the image side and \( \Phi \) is the chromatic weighted angular intensity of the beam at the LMIS,

\[ \Phi = J_0 / E \]

(2)

where \( J = dI / d\theta \) is the angular intensity of ion current emitted by the source and \( \Delta E \) is its FWHM energy spread.
Since the energy spread of the beam, ΔE, increases with total source current, there is no advantage to operating LMIS at high emission currents in the hope of increasing J through an increase in JQ. Maximum values of JQ (and therefore of J) are normally achieved at source currents of only a few μA/σ.

Most practical FIB systems for single species ion beams employ 2 lenses in a condenser/objective combination. Fig 1 shows an ion focusing column in which the LMIS needle and extractor, followed by two accelerating gaps, form a tetrode gun/condenser arrangement, used in combination with a final probe-forming objective. Current density up to 5A/cm², with final beam diameter less than 50nm at 50keV, have been achieved using this so called FIB 50 system. Fig 2 shows a photograph of the lens, together with a scanning ion microscope image showing resolution of better than 50nm.

Columns for mass-selected beams from alloy LMIS should, ideally, utilise a third lens in combination with the mass filter. Wien E×B mass-to-charge ion filters are most commonly used, though one group has achieved considerable success using an all magnetic m/q filter.

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![Fig 1. Schematic of FIB 50 ion focusing column giving probe diameter down to 50nm at 50keV.]

The complexity of the rest of the FIB system will vary considerably with its application. In surface analysis, where samples are normally no more than a few tens of mm in size, but may be of irregular topography, specimen stages of the type found in scanning electron microscopy, with tilt and rotation capability, are normally required. Ultra high vacuum is also usual for techniques such as secondary ion mass spectrometry to be effective. Vacuum requirements are less demanding for most microfabrication applications, but precision XY stages, coupled to sophisticated beam scanning and pattern generation capabilities are essential. Thus, in mask and circuit repair applications, motor driven stages, capable of handling plates of up to 8 inches square are required, while for wafer scale fabrication using FIBL or FIBI, it becomes necessary to use servo-controlled stage drives, employing laser interferometer position measurement systems, capable of giving placement accuracy of better than 0.02 μm.
3 - MICROMACHINING AND DEPOSITION

One of the most successful applications of FIBM and FIBD is in the repair of chromium-on-glass photomasks, as used to pattern each layer of an integrated circuit by optical lithography. Following their manufacture by electron beam lithography, masks often contain deviations from the required pattern due to unwanted chromium (opaque defects) or missing chromium (clear defects).

Laser beams have conventionally been used to remove opaque defects, but as circuit dimensions approach 1 μm and below, laser repair is incapable of achieving the required resolution. Fig 3(a) shows the kind of damage to the photomask, due to melting of both chromium and underlying glass, which is unavoidable using laser repair systems. In contrast, Fig 3(b) shows the much finer repair definition obtainable by FIBM.

One initial drawback of the FIB repair technique was the presence of a stain at the repair site, due to the inevitable implantation of the metallic Ga⁺ ion into the underlying glass of the mask as the chromium of the defect (typically 80nm thick) is sputtered away. (See Fig 4). /11,12/. Fortunately, this can be overcome by spraying an antistaining gas through a nozzle to impinge on the mask plate coincidentally with the Ga⁺ ions. The implanted gallium is thought to combine with the gas molecules, thereby reducing the metallic properties of the stained region and restoring optical transmission as shown in Fig 4. /12/.

Clear defects are repaired by FIBD, using a hydrocarbon gas, again delivered by nozzle at the substrate (Fig 5). The impinging ions decompose the hydrocarbon molecules at the surface of the target to produce a highly adherent film of carbon, which forms an effective opaque patch over clear defects, such as pinholes in the chromium (Fig 6). Deposition efficiency will vary with the gas chosen. This can be seen from Fig 7 which compares the deposition rates possible using an optimised proprietary process, available in a commercial machine, /13,14/ with that achievable using styrene (C₈H₈) as the deposition gas. /15/.
Fig 3. Scanning electron micrographs showing comparison between (a) laser repair and (b) FIB repair of opaque defects on photomasks /11/.

Fig 4. Transmittance of photomask following FIB repair of opaque defect /12,13/
Curve A: gallium implantation stain
Curve B: improved transmittance using antistain process.
Fig 5. Schematic of FIBD process by gas decomposition.

Fig 6. Carbon patch produced by FIBD /14/.

Fig 7. Thickness of carbon deposit, produced by FIBD, as a function of ion dose /14,15/.
In addition to their use in mask repair, FIBM and FIBD are of obvious application to the modification and repair of both part processed and complete integrated circuits. FIBM has been used successfully to cut aluminium track interconnects for the removal of unwanted connections /16–18/ (see Fig 8). To date, there has been less progress on the use of FIBD to repair breaks, but preliminary work on metal FIBD, notably that of Melngailis, Shedd and coworkers /19–21/, using gold bearing gas, indicates that track repair and rework should be feasible.

With these applications in mind, it should be noted that gas assisted FIBM has been successfully employed, using nozzle delivery systems of the kind shown in Fig 5, to deliver a reactive gas in order to accelerate substrate removal. This approach has been used at Osaka University to achieve increases of up to an order of magnitude in aluminium machining rates, using Ga ions, with Cl₂ as the reactive agent. Too high a pressure of chlorine was found to be detrimental and reduced the machining rate below that due to physical sputtering alone. This was, presumably, a consequence of excessive coverage by adsorbed gas molecules, preventing removal of the aluminium substrate atoms /22/.

Use of FIBM for IC repair will require accurate end point detection to allow termination of the micromachining process immediately following removal of the unwanted feature. This must be done precisely enough to prevent damage to underlying layers of the circuit. Depth profiling by dynamic SIMS has been suggested as a way of achieving this. Unfortunately, dynamic recoil mixing of layers by the intense energetic ion beams in FIB technology degrades the sharpness of the metal–substrate interface, making accurate end point detection difficult to achieve by this route /23/. Ion induced secondary electron contrast (ISE) appears, at the time of writing, to offer a simpler, more effective alternative /24/.

Assuming that acceptable end point routines can be established, IC repair probably represents the most significant area of application for FIB technology. In addition to the removal and deposition of tracks, FIB offers the unique capability of resistor trimming. Thus, by removing segments of implanted or thin film resistor elements, it is, in principle, possible to trim resistor values with very high precision, possibly to ppm levels. This is far beyond the precision feasible during normal production processes and could lead to the development of circuits not previously thought possible. Initial work, such as that of Sudraud, has indicated what may be achieved in resistor trimming /16/.

Finally in this section, mention should be made of the role played by the method of scanning the beam in determining the quality of etch pit produced using FIBM. Thus, as the depth of etch increases, redeposited material from the bottom of the trench will build up on the sidewalls, unless removed by repetitive scans.

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**Fig 8.** Variation of sidewall deposition with method of scanning
(a) severe sidewall deposition due to single scan, left to right
(b) reduction of sidewall deposition by multiple scanning, bottom to top (1, 2, 5 and 10 scans) /25/.
This effect is graphically illustrated by the results in Fig 8, which shows the advantage of using multiple scans to avoid sidewall build up /25/. Sidewall deposition has been used to ingenious advantage by the MIT group to effect interconnection between layers in a microcircuit when machining vias in multilayer device structures /20/.

5 - OTHER DEPOSITION TECHNIQUES

5.1 PROXIMITY FOCUSING

Recently, there has been an interest in the use of beams decelerated to energies low enough for sputtering to cease and for deposition of the beam element to occur /26/. This approach is inherently cleaner than gas based FIBD and may be useful in doping of layered deposits in molecular beam epitaxy applications.

An alternative low energy ion beam deposition technique has very recently been developed /27/ using a LMIS in a point-to-plane configuration, similar to the scanning tunneling microscope (STM) electron imaging systems. Such an arrangement, shown schematically in Fig 9, relies upon the low running voltage required for a LMIS when the working distance is very small. In the proximity focusing configuration, the onset voltage for emission is

\[ V_o = \ln \left( \frac{2b}{r_t} \frac{Y}{\varepsilon_0} \right)^{1/2} \]  

for a source of needle radius \( r_t \) and a liquid metal of surface tension \( \gamma \).

The onset voltages predicted by equation (3) are shown in Fig 10, for a range of values of tip radius. It can be seen that needles having \( r_t \) values of 1 \( \mu \)m and lower will operate at voltages below 100 V, provided that tip-to-plane spacings of \( \leq 1\mu m \) can be maintained by accurate servoing of source height \( h \). Under these conditions, net deposition of ions can occur and the system can be used to write patterned tracks by moving the substrate under the beam. Submicron deposits have already been produced in this way.

![Fig 9. Schematic of LMIS used for machining and deposition in proximity focusing mode /27/.](image)
5.2 - MICRODROPLET DEPOSITION

Liquid metal ion sources can produce charged droplets and clusters, which can be focused and scanned by electric lens and deflector systems. Relatively crude arrangements of this type, generating charged gold droplets of up to a few μm in diameter, focused and scanned to produce deposit dimensions as small as 10 μm, were reported at an earlier IPES meeting /28/. Since then, there has been a rekindling of interest in this so-called Focused Droplet Beam (FDB) deposition, notably in Sudraud's group in France, where micron scale deposits have been used for microcircuit repair /29/. Typical deposition rates are ~1 μm/s, which is of the same order as gas phase FIBD.

6 - LITHOGRAPHY AND IMPLANTATION

6.1 FIBL

Focused ion beam lithography (FIBL) makes use of a vector scanned focused ion beam from a LMIS to pattern a microcircuit. The pattern is formed in a layer of ion sensitive polymer coated onto the surface of the wafer of silicon, gallium arsenide, etc. Electron beam lithography (EBL) is already widely used to produce features as small as a few tenths of a micron in VLSI microcircuits. FIBL has two major potential advantages over EBL for this so-called "direct write" lithography process as follows.

i) Typical resists are up to 100 times more sensitive to ion beam exposure than to electron beams /30,31/.

ii) FIBL is not subject to the "proximity effect", due to backscattered electrons from the substrate in EBL, which causes over exposure of resist and limits the separation which can be achieved between adjacent features /32,33/.

Unfortunately, the range of heavy ions from LMIS is much shorter than that of electrons (substantially below 0.1 μm for 70 keV Ga\(^{\text{+}}\) ions in polymethylmethacrylate (PMMA) resist). Because of the difficulty of producing pinhole free resist layers, required with heavy ions, the use of lighter, more penetrating, doubly charged ions, which allow thicker resist layers, is preferred. Thus Si\(^{2+}\) ions, arriving with 140 keV of kinetic energy at the wafer, from a 70 keV mass filtered column, have been successfully used for FIBL, using 0.4 μm thick PMMA
However, as this relatively early work indicated, the edge profile of resist patterns produced by FIBL can be unacceptably ragged when high sensitivity resists are used. This is because ion doses for resist exposure are so small that random statistical noise considerations become non negligible. In practice, therefore, it is not possible to make use of the highest sensitivity resists to enhance writing speeds. Since, in addition, the beam intensities available from EB lithography systems are still more that an order of magnitude greater than those from FIB systems, FIBL does not appear to offer any substantial throughput advantage over EBL.

The second potential advantage of FIBL, however, is practically realisable and the absence of backscattered particles in FIBL allows the lithography of closely packed features with no proximity effect. This is clear from Fig 11, which shows no dependence of line width on spacing, for features as small as 0.1 μm, using 100 keV Ga⁺ FIBL for both positive (PMMA) and negative (steareate based) resists. Linewidth variation for patterning resists on different substrates is also insignificant /35/.

There has been a resurgence of interest in FIBL and recent work includes the use of Be⁺⁺ and Si⁺⁺ from Au-Si-Be LMIS to produce mushroom or T-profile gate electrodes for short channel FET devices /36/. The finest resolution lithography produced to date by FIBL has been performed at Hughes Research Labs, where, using 50 kev Ga⁺ FIBL to expose a bilevel resist structure, 30nm lines on a 150μm pitch have been produced /37/.

![Fig 11. Results of FIBL for positive (PMMA) and negative (steareate) resists showing absence of proximity effect down to 0.1μm features /37/ (100 kev Ga⁺).](image)

6.2 - FIBI

The use of mass selected intense beams of dopant ions derived from alloy LMIS, is one of the most exciting concepts made feasible by FIB technology. It relies upon the availability of reliable alloy LMIS and mass filtered columns as mentioned previously. For example the Au-Si-Be source /10/ permits both p (Be) and n (Si) type dopants for III-V compound semiconductor technology to be produced from a single source and other similar sources have been reported for silicon technology.

One of the first hurdles in the development of FIBI is the comparison of dopant profiles using focused beams with those achieved by standard flood implant processes. Depth profiling of implanted regions indicates only minor differences between FIBI and flood implants, both for GaAs and silicon /38,39/. Some FIBI doping profiles display significant deviation from Gaussian, in the form of a pronounced tail. This is probably due to radiation enhanced migration as a consequence of the much higher dose rates of FIBI /38/. As a further example of enhanced damage effects: while B implants in silicon show no difference in electrical characteristics between FIBI and flood processes, there is a degradation of performance in the case of arsenic FIBI, possibly due to extra damage associated with the heavier ion.
Because of the high intensity of FIB, self-annealing of implanted regions has been postulated and, despite the theoretical doubt cast on this possibility, some experimental evidence has been found, with laser Raman scattering showing reduced damage in the case of FIBI. This is coupled with superior electrical activation efficiency, following furnace annealing.

(Furnace annealing is, incidentally, not ideally suited for very small implanted features, because of loss of resolution due to lateral spreading. Pulsed annealing by lasers or electron beams must be used.)

The future of FIBI will not lie with mass production of silicon or gallium arsenide microcircuits, which, due to process throughput requirements, will continue to be produced by conventional flood implant processing. However, there will almost certainly be several "niche" roles in which FIBI will be used to complement standard processes. A good example of this is the lateral grading of dopant profiles, which is easy to achieve using FIBI, but virtually impossible by the flood beam approach. The technique has been employed for laterally graded MESFETs and vertical NPN transistor features.

The technique for the latter is shown schematically in Fig. 12. Conventional uniform implants lead to Kirk Effect current crowding, with current concentrated near the edges of the emitter. This is made worse using graded profile III, with profile II being better and profile I proving the best of all.

Other radical departures from conventional processing, reported recently, include striped channel FET's or Focused Ion Stripe Transistor (FIST) devices and a complete EPROM device with a narrow FIBI-produced region to reduce the programming voltage.

Even where IC's are ultimately to be manufactured by conventional means, in the interest of production economics, FIBI may well play a role by providing a unique development tool in which the effects of parameters such as dose, energy and placement can be studied systematically, without multiple processing steps, in so called quick-turn-around-time (QTAT) development of tailored devices.

7 - CONCLUSIONS

Focused ion beam technology is of considerable interest for many key aspects of microcircuit development and other microfabrication areas, such as laser mirrors, TEM specimen preparation etc., too numerous and wide ranging to include in this review.

The field emission LMIS has played a key role in the rapid development of FIB technology by providing the high intensity source of ions, without which the development of the subject would have been impossible. Mask and integrated circuit repair are areas in which FIB systems are already being used close to the standard production environment, but there are promising developments in lithography and direct write implantation doping for specialist applications.
ACKNOWLEDGEMENTS

I am grateful to my colleagues Dr P J Heard (Oxford Instruments) and Dr G L R Mair (Athens University) for many stimulating discussions and to Prof R A Lawes, Rutherford Appleton Laboratory, for his encouragement and support of Focused Ion Beam work. Thanks are also due to Dr Tony Bell (Oregon Graduate Centre) for Fig 9. The continuing collaboration of Drs Ahmed and Cleaver (Cambridge University) is gratefully acknowledged.

REFERENCES

/1/ KROHN, V.E. and RINGO, G.R., Appl. Phys. Lett. 27 (1975) 479
/5/ KNAAUER, W., Optic 59 (1981) 335
/6/ KNAAUER, W., Ibid. 54 (1979) 211
/7/ PREWETT, P.D., Vacuum 34 (1984) 931
/13/ MicroTrim Mask Repair System, Oxford Instruments Ltd., Eynsham, UK
/14/ HEARD, P.J. and PREWETT, P.D., unpublished results
/18/ HARRIOTT, L.R., SCOTTI, R.E. and AMBROSE, A.F., Appl. Phys. Lett. 48 (1986) 1704
/40/ BROWN, W.L. and WAGNER, A., ISIAT '83/IPAT '83, ed Takagi T. (IEEE, Tokyo, 1983) 1738A
/45/ SHUKURI, S., WADA, Y., HAGURARA, K., KOMORI, and TAMURA, M., Ibid. 1264