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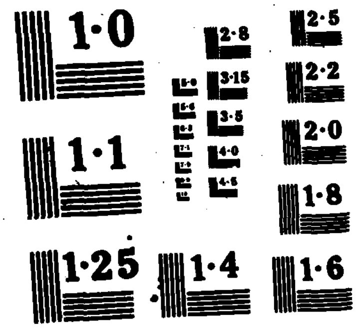

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FOCUSED ION BEAM TECHNOLOGY

John Melngailis

Abstract

The finely focused ion beam is a new instrument with many uses. It can focus a beam of any one of many species of ions at energies up to 200 kV to dimensions below 0.1 μm. This capability can be used: to implant dopants in semiconductors in a maskless process, to mill away material and repair masks or circuits, to deposit material with submicron resolution if an appropriate local gas ambient is present, to perform lithography by exposing resist, and to analyze and examine specimens. There are about 30 sophisticated systems in operation world wide, about two thirds of them in Japan. The field is still in its infancy, and one can expect both improvements in machinery and many new applications to develop particularly in the area of custom semiconductor devices.

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Focused Ion Beam Technology*

by

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Abstract

The finely focused ion beam is a new instrument with many uses. It can focus a beam of any one of many species of ions at energies up to 200 kV to dimensions below 0.1 μm. *This capability can be used:* to implant dopants in semiconductors in a maskless process, to mill away material and repair masks or circuits, to deposit material with submicron resolution if an appropriate local gas ambient is present, to perform lithography by exposing resist, and to analyze and examine specimens. There are about 30 sophisticated systems in operation world wide about two thirds of them in Japan. The field is still in its infancy; and one can expect both improvements in machinery and many new applications to develop particularly in the area of custom semiconductor devices.

* Supported by Draper Laboratory (contract DLH-225270), DARPA (contract MDA903-85-C0215), Joint Services Electronics Program (contract DAAG29-83-k-0003), and Nippon Telephone and Telegraph.

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Focused-Ion-Beam Technology

Not since the laser has a new instrument appeared with as many uses as the finely focused ion beam. These uses range from maskless, resistless fabrication of integrated circuits to microanalysis of prehistoric artifacts. At present ion beams of any number of ion species, among them the dopants of Si and GaAs, can be focused to dimensions below 0.1 μm at accelerating voltages of up to 200 kV and current densities in the focal spot on the sample of 1 A/cm^2. Energetic ions (10 keV to 200 keV) incident on a solid can: imbed themselves to produce doping, cause surface atoms to be sputtered off, cause electrons to be emitted, induce chemical reactions, and produce lattice damage. These many effects have led to many applications. The main driving force for the development of this technology, however, has come from the potential impact on semiconductor device fabrication.

Although the earliest development of sophisticated focused ion beam systems occurred in the U.S. at the Hughes Research Laboratories[(1)(2)] the largest volume of research work in the field is now being done in Japan. All of the major integrated circuit manufacturers in Japan have mounted research efforts, and a total of about 20 machines are in operation. While a total of eight companies manufacturing these machines have sprung up in the U.S., in Great Britain, and in Japan, only JEOL in Japan can be considered in a production mode. JEOL has delivered a total of 15 machines, all domestically. At this point the others have delivered at most one or two machines each.

Equipment

A focused ion beam machine has three major parts: the source of ions, the ion optical column, which focuses the beam and in some cases mass separates ions; and the sample stage and beam deflection system. It resembles an electron beam lithography system both in operation and in principle, except that ions instead of electrons are focused on to the sample.

The development of the high brightness liquid metal ion source in 1975[3] was the single most important factor in launching this technology. Before that in 1973 ions from an implanter had been focused and many of the potential applications had been demonstrated or postulated.[4] However, the current of ions in the focal spot was discouragingly low. The liquid metal field ionization source boosted this current density by 4 orders of mangnitude. In this source a liquid metal film is made to flow down a sharp needle (usually tungsten) from a reservoir, see Figs. 1 & 2. The needle faces an extraction electrode which produces a high electric field at the sharp tip. since the electric field is acting on a liquid conductor, this conductor further deforms to produce an even sharper cone. The apex of this cone is the source of ions. Sources of many elements, either pure or in alloys, have been developed. Ga is the most commonly used, AuSi, PtB, AuBeSi are some of the others. The lifetime of these sources is in some cases 100 hours or more.

The ion optical column is a stack of precision-machined electrostatic lenses and other elements, see Fig. 2. In the simplest case, where single element sources are used, the column can be a single lens and beam deflector[1]. With alloy sources, a mass separation element, usually consisting of crossed electric and magnetic fields, is used in conjunction with two or three lenses.[2] The most advanced column of this type built to date, Fig. 3, has operated at voltages up to 200 kV, and demonstrated beam diameters below 0.1 μm.[5] The operation of the column is shown schematically in Fig. 2.

This offers great flexibility and simplicity. With no need for resist or lithography one can in a single step vary the implantation dose from transistor to transistor on a chip, or one can vary the dose as a function of position within a transistor.[6] This may lead to novel devices. The price for this flexibility is lower throughput. The focused ion beam implants point by point. With a 0.1 μm diameter beam, an area of 1 cm^2 can be implanted to a dose of, say, 6×10^{11} ions/cm^2, which is typical of a MOS channel implant, in 17 min. Source and drain implants are 3 orders of magnitude higher and would be practical over only very limited areas. While standard large area fabrication will not be replaced, the door has been opened to special applications, device customization, or prototyping.

(2) Ion milling. If the ion beam scans an area for a long time, material is sputtered away. A typical removal rate with a 0.1 μm diameter beam is about 1 μm^3/min. Even though this is slow, and only very limited areas can be milled to any significant depth, very exciting applications exist. Milling with focused ion beams proves to be well suited for photomask repair of both opaque and clear defects.[7] This is likely to be the first large scale commercial use of focused ion beam. Three companies are offering mask repair machines.[8] A similar application is integrated circuit repair. Here, by milling away part of a metal film connections can be broken [9][10], and by special techniques connections can also be made [10] see Fig 4. As will be discussed below, the focused ion beam can be used as a scanning microscope to display the mask or circuit

before or after repaired. Thus these applications become even more attractive.

(3) Ion assisted etching. If a gas ambient such as chlorine is produced near the surface of, say, Si or GaAs, then material is removed where the ion beam is incident.[11] As a result of the ion induced chemical reaction, the rate of removal is 5 to 10 times faster than by milling alone.

(4) Ion assisted deposition. This is the reverse of etching. When a gas ambient of $Al(CH_3)_3$ or WF_6 is created at the surface, a deposition of an Al/C/O mixture or of tungsten is observed where the ion beam is incident.[12] Submicron width lines have been deposited. This capability of material addition can be used to repair opaque defects in photo masks,[9] and potentially in x-ray lithography masks. Even more exciting is the possibility of repairing integrated circuits by adding conducting films. In fact, since the deposition rate can be fast (a dose of 10^{16} to 10^{17} ions/cm^2 can produce a usable film thickness), the wiring up of prototype integrated circuits such as gate arrays is possible.

(5) Lithography. The use of focused ion beams to expose resist is quite similar to electron beam lithography. Resists such as PMMA are about 100 times more sensitive to ions than to electrons in terms of charge per unit area. In addition, the ions deposit their energy and expose the resist in a tight cone or cylinder around the point of entry, while electrons scatter over a wider area and can produce unwanted widening of features. The finite range of ions, however, limits the resist thickness. Light ions and high voltages reduce

this limitation. A 200 kV machine operated with Be^+ ions has exposed 0.8 μm thick PMMA[5]. Special cryogenic sources of ions which can emit hydrogen or helium ions are being developed[14] and are particularly attractive for lithography.

(6) Microanalysis. If a mass spectrometer is positioned to pick up the species that are sputtered off by the focused ion beam, then one can analyze the composition of solids with submicrometer resolution. This is a high resolution SIMS (secondary ion mass spectroscopy) machine. The location of the elements, can be displayed on a CRT (cathode ray tube). The composition of meteorites, integrated circuits, and and ancient fabrics has been studied.[15]

(7) Scanning ion microscopy. When a beam of ions is scanned over a surface, electrons are emitted from the impact point 6f. These electrons are collected in a suitable multiplier tube whose output then modulates a CRT. The image formed is similar to that of a scanning electron microscope. The scanning ion microscope clearly erodes the sample examined. However, a photograph can be taken with a loss of less than a monolayer of material. Also erosion can be minimized by using computer image storage techniques.

The Future:

The focused ion beam field is still in its infancy. In addition to the demonstrated applications discussed above, others can be imagined. Focused ion beam fabrication may permit a larger variety of devices to be fabricated on integrated circuits than current technology permits. One example might be, electronic devices combined with optical or sensor devices on single chip.

One can also speculate about all vacuum fabrication, where a large number of fabrication steps would be carried out in a single vacuum chamber. The focused ion beam, by eliminating the need for resist, would play a central role in such a system. The first step in this direction has been taken at the Optoelectronic Joint Research Laboratory in Japan where a focused ion beam column and a molecular beam epitaxy system share the same vacuum chamber.(17)

The ion beam column will also be improved. Lenses designed to reduce chromatic abberation are projected to increase the current density by two orders of magnitude and decrease the beam size by a factor of 3.(17) In addition, the present throughput limitation of focused ion beams may be overcome for repetitive structures by the use of multiple beamlets deflected synchronously. Such operation has already been demonstrated.(18)

The finely focused ion beam has opened a broad and exciting field of research. The first fruits of research in this field are beginning to be harvested by the integrated circuits industry in the development of photomask repair machinery. Others are still ripening.

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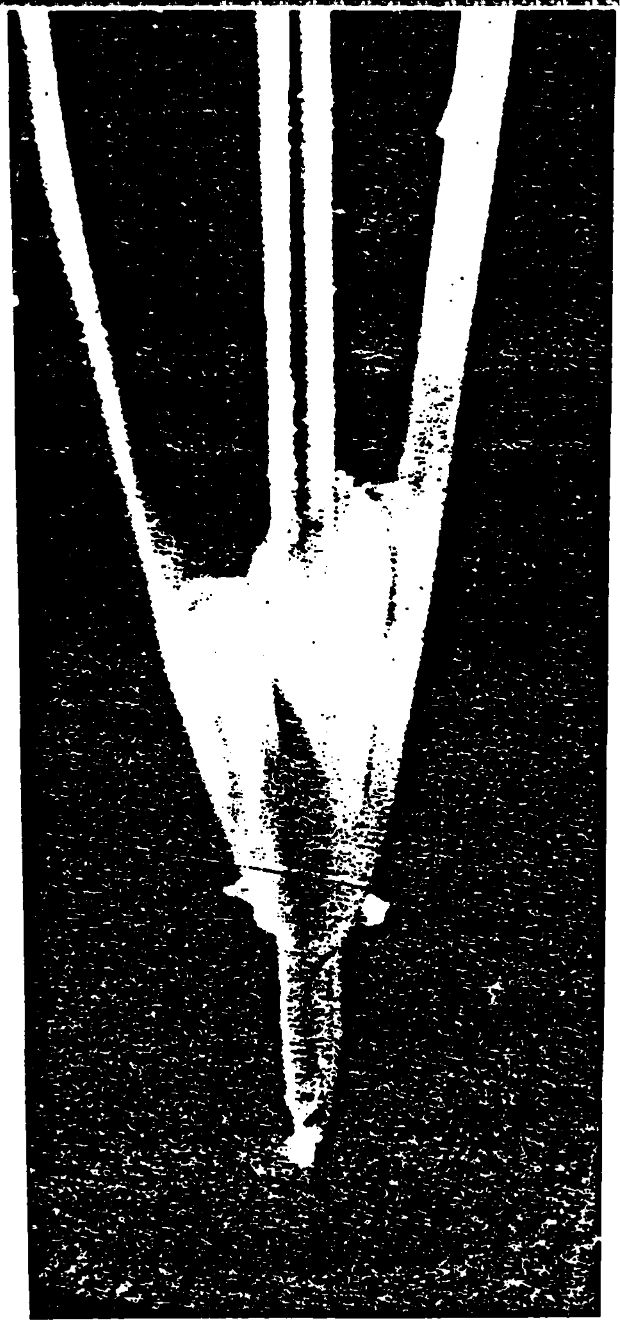

Fig. 1 Liquid metal ion source operating in a test fixture. (Photo from Ion Beam Technologies Inc.) Blue light is emitted from the area near the tip of the needle, which is the source of ions. The drop of liquid gallium is held by surface tension between the U-shaped heater ribbon and the shank of the needle. The shank of the needle is 0.27 mm in diameter.

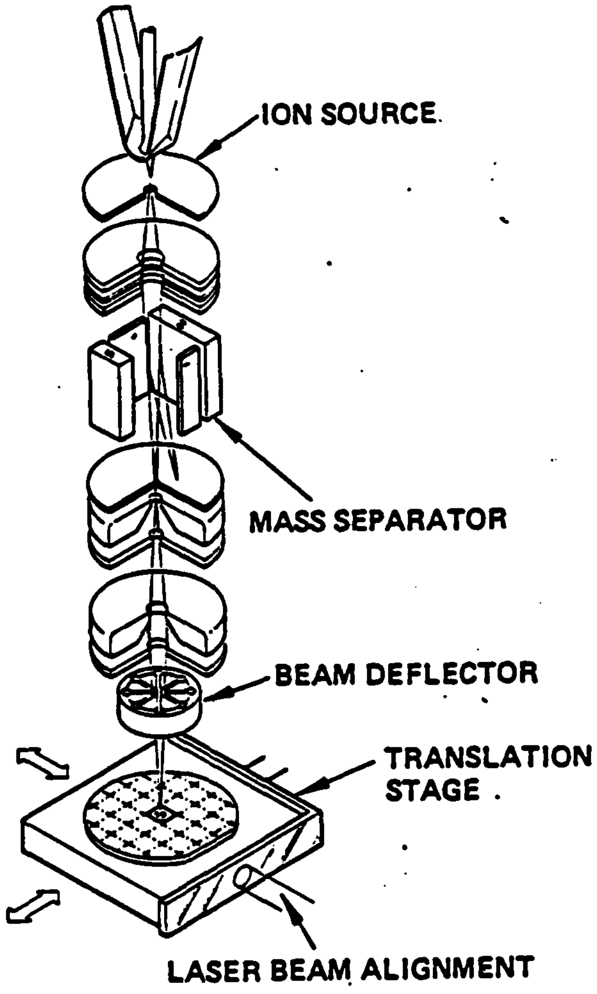

Fig. 2 Schematic of a focused ion beam system. (from Hughes Research Laboratories)

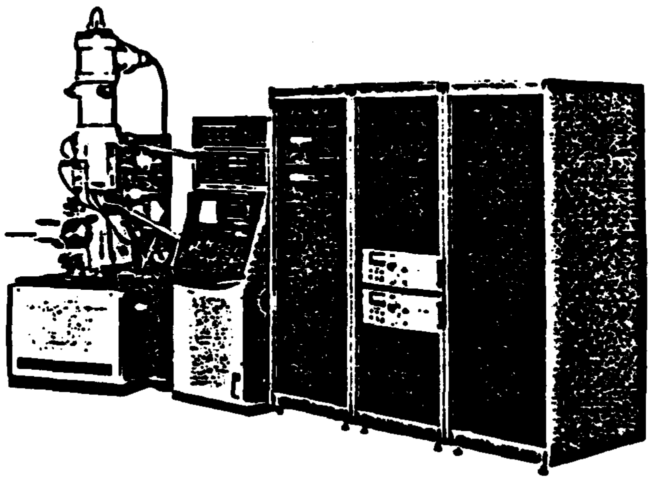

Fig. 3 A photography of the 200 kV focused ion beam system (ref. 5) built by The Institute of Physical and Chemical Research in Saitama, Osaka University, and JEOL. The large upright cylinder contains the column and source the sample stage is at the base of the column and the pumping system is in the square cabinet on which the column rests.

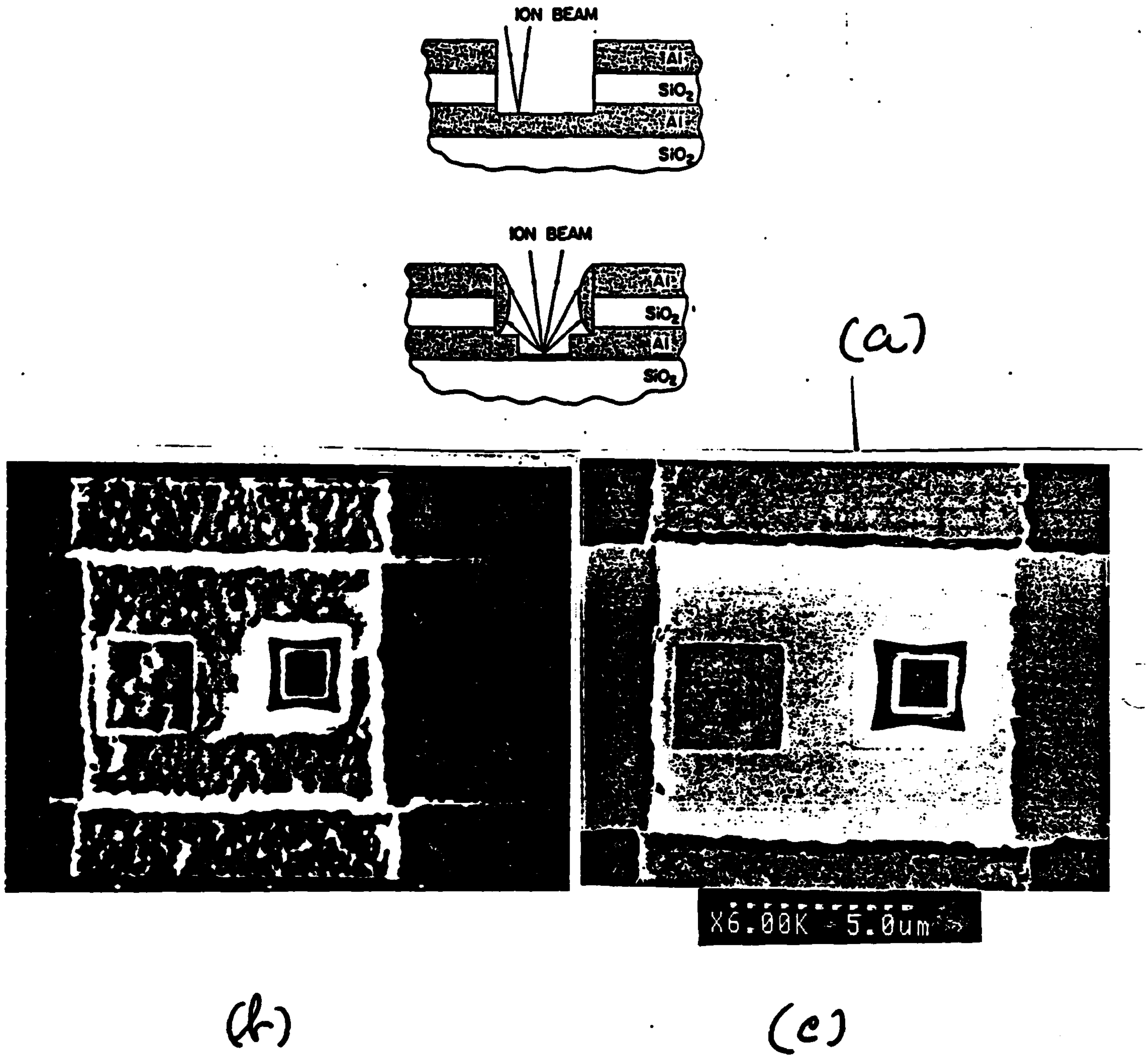

Fig. 4 Shows the creation of a short circuit between two conducting films separated by an insulator. Ref. 11.

a) Schematic of the process in cross section. A square pit is first milled through top metal layer, through the insulator, and part way into the second metal layer. Then a smaller square pit is milled concentric with the first one and the sputtered off metal redeposits on the sidewalls.

b) Scanning ion micrograph after the process has been carried out. Square at left shows first step discribed in a) milled for purposes of comparison and on the right is the completed short. The slightly bowed in side walls are produced by the redeposition. This connection had a resistance of 0.4 Ω. The pit measures 3 μm x 3 μm. Connections have also been made with pits of dimensions below 1 μm.

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