

Chapter 3. Focused Ion Beam Fabrication

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3.1 Focused Ion Beam Fabrication

Research in focused ion beam applications is being conducted on two types of machines. The first system has mass separation and can produce beams of the dopants of Si and GaAs with diameters below 0.1 μm . This system, which is used for ion implantation and lithography, operates at voltages up to 150 kV, has sophisticated pattern generation software, and can accept up to five inch substrates. The second, simpler system has no mass separation and is operated with Ga^+ ions at energies up to 50 keV and minimum beam diameters of 0.06 μm . It is mounted on an ultrahigh vacuum system and has a sample stage which can be heated. This system is mainly used for ion induced deposition and milling.

3.2 Development of Focused Ion Beam Implantation and Lithography

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Project Staff

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To apply ion beam implantation and lithography to integrated circuit fabrication, one must align the pattern to be written to existing features on the wafer. One must also generate this pattern from computer aided design. Accordingly, we have developed and refined the capability to transfer the patterns of any given level of an integrated circuit layout from the computer-aided design software in use at MIT, called

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MAGIC, to the focused ion beam system. Different ion doses or dose gradients can be assigned to each rectangle of the design. This permits a wafer to be processed to a given step in the standard integrated circuits facility, transferred to the focused ion beam for implantation or for ultrafine lithography, and then transferred back to complete the fabrication.

Alignment is carried out by imaging alignment marks on the wafer using the scanning ion microscope mode. In addition, beam deflection routines have been developed which calibrate beam deflection, stage motion, and correct for axis non-orthogonality. We have placed features on a wafer aligned to $\pm 0.1 \mu\text{m}$. The overall capability that we have developed is essential to our implantation and lithography projects.

3.3 Frequency Tunable Gunn Diodes Fabricated by Focused Ion Beam Implantation

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Project Staff

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We have developed frequency tunable Gunn diodes which consist of two contacts on a GaAs surface. A conducting channel, which has a gradient of doping in the direction of current flow, runs between the two contacts. The frequency can be tuned from 6 to 23 GHz by varying the bias voltage by about 12 V. The power output of the devices is in the -3 to -4 dBm range. A Gunn diode with uniform doping shows very little variation of frequency with bias. Many gradients of doping were implanted by programming the focused ion beam system appropriately. In

addition, measurements were made of the percent of activation as a function of implanted dose. Since this percentage decreases with increasing dose, a linear gradient of dose does not imply a linear gradient of doping or of resistivity. The devices have been modeled using a computer program based on the Boltzmann transport equation. The tunable Gunn diodes may prove useful for special radars such as those used in collision avoidance.

3.4 NMOS Transistors with Focused Ion Beam Implanted Channel Regions

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Project Staff

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NMOS transistors with gate lengths from $1.6 \mu\text{m}$ to $10 \mu\text{m}$ were fabricated in the integrated circuits facility. Focused ion beam implantation was substituted for the threshold and punch-through control implants. Both boron and arsenic were implanted and both the geometry of the implant and the dose were varied. A total of 1,920 combinations of variables were fabricated in duplicate on the wafer. Four wafers were processed to verify reproductibility. NMOS transistors with a line implant (0.1 to $0.2 \mu\text{m}$ wide) adjacent to the source were compared to devices with no implant. A small increase in transconductance and a large increase in output conductance were observed. This resulted in a factor of twenty increase in open circuit gain. This result demonstrates the use of the focused ion beam to economically explore novel device concepts over a wide range of variables.

3.5 GaAs MESFETs Fabricated with Focused Ion Beam Channel Implants

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We expect GaAs MESFETs with a gradient of doping from source to drain to show improved performance. This is of particular interest for short gates. We have designed and fabricated a mask set to explore a wide variety of transistor structures. The contacts and longer gates will be fabricated by conventional optical lithography using these masks. Ultra short gates (below $0.1 \mu\text{m}$) will be fabricated using the focused ion beam to expose the resist. The penetration of ions into the substrate during the resist exposure is an undesirable side effect. A technique to overcome this has been developed and tested using a film of Si_3N_4 on the GaAs substrate under the resist. The film prevents ion penetration and damage, yet can be etched to apply the contact.

3.6 Focused Ion Beam Exposure of Resists

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The goal of this program is to generate known resist profiles for the purpose of studying their effect on plasma etched features. Optical lithography can be used down to about $1 \mu\text{m}$. Below that, focused ion beam lithography will be used. So far, we have exposed features down to $0.05 \mu\text{m}$ in PMMA in $0.3 \mu\text{m}$ thick resist with vertical sidewalls. These were made into x-ray lithography masks in collaboration with the MIT

Submicron Structures Laboratory. We are seeking other focused ion beam resists besides PMMA. We have used Shipley SAL 601 negative resist to also expose features down to $0.1 \mu\text{m}$. However, this is less desirable since profile control in negative resists is difficult. Microport 2400 which is a positive e-beam resist was also tried but was found to have a small exposure window, i.e., less than a factor of two between threshold exposure and cross linking. Other candidates are being considered. The profile development will be modelled using TRIM programs for ion penetration and SAMPLE for resist dissolution.

3.7 Focused Ion Beam Induced Deposition of Low Resistivity Gold Structures

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A local gas ambient is created in vacuum on a sample surface by aiming a gas feed capillary tube at the surface in close proximity. For gold depositions we use a gas of $\text{C}_7\text{H}_7\text{F}_6\text{O}_2\text{Au}$. Deposition occurs when a focused ion beam is scanned on the surface in the area of the gas ambient. Ion induced deposition permits fabrication of deposited features at dimensions much finer than those achieved by laser induced deposition. Ion induced deposition is already in commercial use for repair of photolithography masks. If conducting films can be deposited, this process will be used for local repair and restructuring of integrated circuits. Also, high aspect ratio structures (thick with steep side walls) can be deposited, the repair of x-ray lithography mask will become possible.

We have deposited gold lines down to $0.1 \mu\text{m}$ width and patches $3 \times 3 \mu\text{m}$ of $1 \mu\text{m}$ thickness with steep side walls. The microstructure of the gold films has been studied by transmission electron microscopy. The

films grow in discontinuous, ball-like structures at the early stages and in columns as they thicken. Some features have been deposited on actual x-ray lithography masks and tested at the Fraunhofer Institute in Berlin. In spite of the structure, the x-ray opacity of films 0.8 μm thick was found to be sufficient for normal mask exposure.

When the substrate is heated to about 120°C, the structure of the deposited films is observed to change. In addition, the resistivity is found to drop from a value of $\sim 1000 \mu\Omega\text{cm}$ to a value below $10 \mu\Omega\text{cm}$, i.e., near the bulk value for gold of $2.4 \mu\Omega\text{cm}$. This is the first deposition of low resistivity metal film by this process. Low resistivity is needed for application of focused ion beam induced deposition to integrated circuit restructuring and repair.

3.8 Fundamental Properties of Ion Induced Deposition

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The ion induced deposition of gold from dimethylgold hexafluoro acetylacetonate has been studied using noble gas ions from an implanter. Although the instantaneous current density in a focused ion beam is about five orders of magnitude higher than that from a broad implanter beam, the fundamental principles of the process are the same. In the case of a focused ion beam, the beam is usually scanned rapidly over a given area so that the average current density is more nearly comparable. In going from Ne to Xe, the yield (atoms deposited/incident ion) is found to increase. The yield correlates better with nuclear stopping power than with electronic stopping power. In addition, the sputtering yield for each ion species was measured.

The mechanism by which the ion transfers energy to a molecule adsorbed on the surface is not clear. It is not direct ion-molecule impact because the cross section is too large. The substrate must participate. We are attempting to model the process using the TRIM program to calculate the energy distribution of surface atoms as a function of distance from the point of ion impact. The yield measurements are being carried out at room temperature, where the films are known to contain carbon, as well as at 120°C (where the films are much purer and their resistivities are nearly equal to the bulk gold values).

3.9 In-Situ Measurement of Gas Adsorption and Ion Induced Deposition

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IBM General Technologies Division
IBM Research Division

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We have constructed a special apparatus to measure gas adsorption and ion induced deposition. The apparatus consists of an ultrahigh vacuum chamber with an ion gun having energies from 0.1 to 10 keV. The sample is a quartz crystal microbalance which can measure the gas adsorption as well as the film growth during ion induced deposition. The gas used is dimethylgold hexafluoro acetylacetonate ($\text{C}_7\text{H}_7\text{F}_6\text{O}_2\text{Au}$) and a monolayer is found to be adsorbed above 1 mTorr pressure. If the sample is cooled below room temperature and the gas pressure is raised above 100 mTorr, then a thicker layer of adsorbate is formed. The yield of atoms deposited per incident ion can be rapidly measured. The cross section for decomposition was found to be $2 \times 10^{-13} \text{ cm}^2$ for 5 keV Ar^+ ions. The deposition is a competition between sputtering and gas molecule decomposition. Contrary to our observations of ion induced deposition with high energy beams (30-100 keV) at these lower energies, relatively pure gold films can be deposited even at room temperature.

3.10 Focused Ion Beam Induced Deposition of Platinum

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Focused ion beam induced deposition of platinum from a precursor gas of (Methylcyclopentadienyl) - Platinumtrimethyl has been demonstrated. This organometallic is solid at room temperature with a vapor pressure of 0.06 Torr. A Ga^+ ion beam at 35 keV has been used. The resistivity and composition of the film and the deposition yield have been studied as a function of ion current density, line dose, substrate temperature, geometry, and supplementary hydrogen pressure. Yield varied from 0.2 to 30, and resistivity varied from 70 to 700 $\mu\Omega\text{cm}$ depending on the conditions. The lowest resistivity was observed at the highest current density: 0.22 nA at 500 cm/sec scan speed repeated over a 350 μm long line. The minimum linewidth observed so far is 0.3 μm , and the deposited platinum is found to be smooth. Auger analysis showed the films to contain carbon. The addition of hydrogen gas supplied to the same area by a second nozzle was found to have little effect on yield or resistivity. Although the deposition of gold from an organometallic precursor on a heated substrate results in low resistivity films, in the case of platinum this is not observed; in fact deposition yield drops to zero as the temperature is raised.

Deposition was also carried out in a focused ion beam milled groove 0.65 μm deep. The yield was found to be 34 at the bottom of the groove and decreased as the groove was filled in.

Focused ion beams induced deposition of platinum is of interest for circuit restructuring and repair because (1) the films have the lowest resistivity reported so far for deposition at room temperature and (2) platinum, unlike gold, is compatible with silicon device

fabrication. Platinum deposition is also expected to be useful for x-ray lithography mask repair because the x-ray absorption of platinum is slightly higher than that of gold or tungsten.

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