Chapter 3. Focused Ion Beam Fabrication

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3.1 Focused Ion Beam Fabrication

The focused ion beam research program at MIT has developed around two machines: a high energy 150 kV system used mainly for implantation and lithography and a 50 kV system used mainly for development of processes related to repair of masks and integrated circuits. The high energy system includes automated patterning capability over wafers up to six inches in diameter. Alignment of the focused ion beam writing to within ± 0.1 μm of existing features on a wafer has been demonstrated. Software has been developed which permits patterns to be transferred from the layout system used in the Microsystems Technologies Laboratory to the focused ion beam machine. Accordingly, this permits flexible, mixed fabrication where standard steps have been carried out in the integrated circuits laboratory at MIT and special implantation or lithography steps have been carried out on the focused ion beam system. Similar mixed fabrication has also been carried out with Ford Aerospace and with Raytheon Research Laboratory. The ion species available for implantation include the principal dopants of GaAs and of Si. The minimum beam diameter available is on the order of 0.1 μm at an ion current of 20 pA. In many of the implantation projects where the minimum diameter is not needed, a higher beam current can be used.

The lower energy 50 kV system has mainly been used to develop ion induced deposition. This technique uses a local ambient of a precursor gas, usually organometallic or metal halide, to permit deposition to be carried out with minimum linewidth of 0.1 mm. The local patterned deposition complements material removal by ion milling and is used to add missing absorber material in the repair of photomasks and x-ray lithography masks or to rewire local connections in integrated circuits. Our efforts have focused on gold and platinum deposition and on understanding the fundamentals of the process.

3.2 Tunable Gunn Diode

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Defense Advanced Research Projects Agency/
U.S. Army Research Office
Contract DAAL03-88-K-0108

Project Staff

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A tunable Gunn diode has been designed and built using the focused ion beam to implant a doping gradient in the direction of current flow. The output frequency of the diode changes from 6 to 23 GHz as the DC bias across the device is varied. The output power is in the range of −10 to −15 dBm. The devices have been extensively tested at M/ACom. Significant power in the second and

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third harmonics has been measured. Using a special high speed oscilloscope, the waveform of the output has been observed. It agrees with the triangular forms predicted by simulations. The potential applications of the tunable Gunn diode, which have been identified as a result of those tests, include collision avoidance radans, electronic countermeasures, and built-in frequency response test circuits for GaAs monolithic microwave integrated circuits.

3.3 Light Emission From Tunable Gunn Diodes

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Contract DAAL03-88-K-0108

Project Staff

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Somewhat surprisingly, we have observed light emission from the tunable Gunn diodes when they are oscillating. The light comes only from the rectangular area where the Gunn domain is propagating. As the frequency is changed, the length of the rectangle changes. The spectrum of the light is roughly Gaussian with some structure and peaks at about 1.3 eV, which is below the 1.43 eV bandgap. The tail of the spectrum extends into the visible. The mechanism of emission is thought to be avalance breakdown and the shift in the spectrum away from the band gap is attributed to local heating.

3.4 Effect of Dose Rate on Activation of Si Implanted in GaAs

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Contract DAAL03-88-K-0108

Project Staff

Henri J. Lezec, Christian R. Musil, Mark I. Shepard, Leonard J. Mahoney, John D. Woodhouse,[4] Dr. John Melngailis

The instantaneous current density in focused ion beam implantation is typically between 0.1 and 3 A/cm^2 while in conventional broad beam implantation the current density is in the range of μA/cm^2. We have found that in the case of Si ion implantation into GaAs this large difference in current density leads to differences in the properties of the material. The implantations were generally carried out at 140 and 280 keV and with doses varying from 1×10^{12} to 1×10^{14} ions/cm^2. SIMS analysis indicates that the broad beam implants penetrate somewhat deeper than the focused ion beam implants. This is thought to be due to the fact that the high current density of the focused ion beam causes amorphization to occur at lower doses than in the broad beam case. Thus channeling would be inhibited for focused ion beam implantation. In addition, the sheet resistance of conventionally implanted material saturates at a dose of about 10^{13} ions/cm^2 while for the focused ion beam implants the sheet resistance (after anneal) actually decreases above 10^{13} ions/cm^2. This has been further examined by Hall sectioning. The drop-off in sheet resistance appears to be mainly due to a lack of activated carriers above doses of 10^{13} ions/cm^2, i.e., in the case of broad beam implantation the carrier density saturates at 10^{18} ions/cm^3, while for focused ion beams it actually drops. Thus for practical applications the focused ion beam dose should be kept below 10^{13} ions/cm^2, or the beam should be scanned rapidly over the area implanted.

[4] MIT Lincoln Laboratory, Lexington, Massachusetts.

3.5 Focused Ion Beam Implantation of GaAs MMICs and MESFETs

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A potentially cost effective application of focused ion beams is the implantation of GaAs monolithic microwave integrated circuits (MMICs). In some cases MMICs require as many as five implantation steps to be carried out during fabrication, and the area implanted in each step may be small. With a focused ion beam system, all implantations can be carried out in one step. Because high resolution is not needed and a high current ion beam can be used, the focused ion beam implantation times are expected to be acceptable. The first device patterns have been transferred from Raytheon to MIT, the alignment capability verified, and the first devices implanted.

3.6 Doping Gradients in GaAs MESFETs

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Contract DAAL-03-88-0108

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Focused ion beam implantation permits the dose to be varied from point to point with a resolution of 0.1 μm. This may permit device optimization. GaAs MESFETs with graded dopant distributions under 0.5 μm-long gate electrodes have been fabricated. When compared with the conventional constant channel implant, increasing the doping towards the source is found to significantly increase transconductance (up to 60%) with little effect on gate capacitance or drain current. Reversing the gradient has the potential to increase power handling capabilities by increasing the gate-drain breakdown voltage. Carrier dynamics including Gunn oscillations have been simulated using a nonstationary, hydrodynamic solution to the Boltzman transport equation which takes into account short channel effects. These simulations have been effectively used to visualize the influence of doping gradients and formation of domains. Using the focused ion beam to also expose resist and define the gate, gate lengths down to 0.1 μm have been fabricated.

3.7 CMOS Transistors Fabricated by Focused Ion Beam Implantation and Lithography

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Defense Advanced Research Projects Agency/
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Contract DAAL-03-88-0108

Project Staff

James E. Murguia, Mark I. Shepard, Professor Dimitri A. Antoniadis, Dr. John Melngailis

Focused ion beam implantation has been used to dope the channels of both NMOS and PMOS transistors. A large number of geometries and doses have been fabricated and tested. For example, in NMOS devices, implantation of a line dose of boron adjacent to the source causes the maximum electric field to appear next to the source rather than next to the drain. This results in a 20% increase in transconductance and a more than ten-fold decrease in output conductance. The result of the boron implant is a 20-fold increase in open circuit gain. One of the key features of this work was the precise ($\pm$0.1 μm) alignment of the focused ion beam implant to the structures fabricated by conventional optical lithography.

To fabricate short gates in the Integrated Circuits Laboratory, a process has been developed which permits combined focused ion beam lithography and optical lithography. The focused ion beam is used only to expose the gate, while all of the other exposures are carried out with conventional lithography. Standard KTI-820 resist is used which is positive in optical lithography but negative when exposed by the ion beam (i.e., the exposed area does not develop out). With this process, transis-

[5] Raytheon Research Laboratory, Lexington, Massachusetts.

tors with gate lengths down to 0.2 μm have been made on top of an optical lithography process which supports minimum dimensions of 1.75 μm.

3.8 Charge Coupled Devices with Focused Ion Beam Implanted Doping Gradients in the Channel

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Defense Advanced Research Projects Agency/
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MIT Lincoln Laboratory
Innovative Research Program

Project Staff

Dr. Analisa L. Lattes,[6] Dr. Scott C. Munroe,[6] James E. Murguia, Mark I. Shepard, Dr. John Melngailis

The main factor that determines the charge transfer efficiency and the maximum clocking speed of CCDs is the time taken by the residual charge to diffuse from one well to its neighboring, lower potential well. This is particularly true in longer channel CCDs. If a slight doping gradient is implanted in the direction of current flow, then a built in electric field is created which will speed up the charge transfer. CCDs with 26-μm-long channels were fabricated in which the doping gradient was created with an As implant dose varying from 0 to 1.5×10^{11} ions/cm^2. The gradient implanted CCDs had a maximum clocking frequency of 41 MHz while the uniformly implanted devices had a maximum clocking frequency of only 2.5 MHz. Such long channel CCDs are used in infrared detectors and in some signal processing applications.

3.9 Focused Ion Beam Lithography

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SEMATECH
Contract 90-MC-503

Project Staff

Jeung-Soo Huh, Haralabos Papadopoulos, Mark I. Shepard, Dr. John Melngailis

A number of resists have been exposed with Be and Si ions at various energies to determine their suitability for focused ion beam lithography. The resists included PMMA, Microposit 2400, HEBR, and KTI 820. Both Microposit and HEBR act as positive resist, for low doses but become negative resists at higher doses due to cross linking. Unfortunately, the window between the positive and negative operation is only about a factor of 2, making them unsuitable for most applications. KTI acts as a negative resist and features down to 0.2 μm line width have been successfully exposed. PMMA, in which we have in the past succeeded in exposing 0.05 μm wide features, acts as a positive resist and was tested here for its sensitivity and ion penetration range. Be ions at 200 keV expose PMMA to a depth of 1.2 μm, while Si ions at 200 keV expose PMMA to a depth of 0.5 μm. We are in the process of testing other resists such as Ray PF. Preliminary results indicate that it acts as a positive resist with a factor of about 10 higher sensitivity than PMMA.

3.10 Focused Ion Beam Exposure Combined With Silylation

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SEMATECH
Contract 90-MC-503

Project Staff

Dr. Mark Hartney,[6] Dr. David C. Shaver,[6] Mark I. Shepard, Jeung-Soo Huh, Dr. John Melngailis

In the silylation process the top layer of a resist such as SAL 601 from Shipley is cross linked by exposing it with a dose of ions. The resist is then exposed to a silylating agent in gaseous form which diffuses onto the surface where it is not cross linked. The resist is "developed" by reactive ion etching in oxygen which removes the resist that had been exposed by the ions. This process is sketched out in figure 1. Since only the top surface of the resist needs to be cross linked, the range of ions is unimportant. As a result, we have successfully used Be, Si, Au and Ga ions. The minimum dose needed to expose is 1×10^{12} ions/cm^2 for the heavier ions, i.e., about an order of magnitude lower than required for PMMA. Thus Ga ions can be used which have a current density in the beam an order of magnitude higher than the lighter ions. Proximity effects were

[6] MIT Lincoln Laboratory, Lexington, Massachusetts.

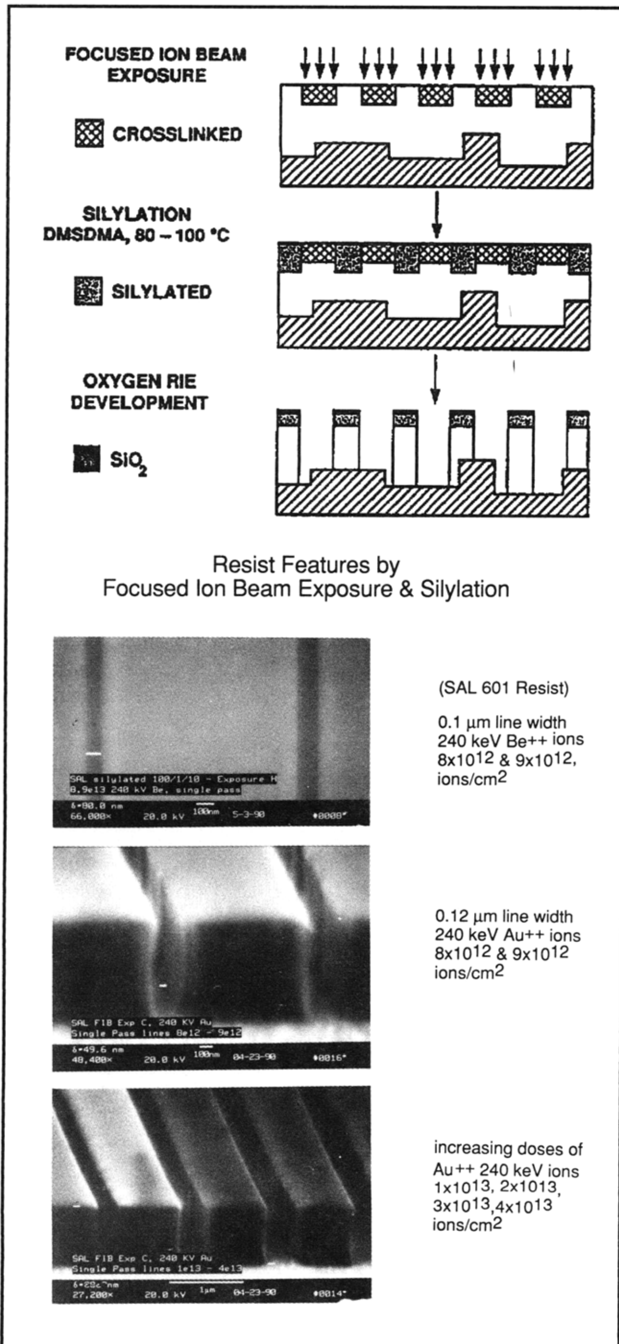

Figure 1. (Top) Schematic of the silylation process. Where the ions strike, the resist becomes cross linked, impeding the silylation. Reactive ion etching then removes the unsilylated resist. (Bottom) Series of scanning electron micographs of the resist features. First, top view of lines exposed with 240 keV Be^{++} ions showing smooth sidewalls and lines of 0.08 μm and 0.1 μm width. Second, resist lines of about 0.15 μm width in profile exposed with 240 keV Au ions. The resist sidewalls are almost vertical. Third, profiles of resist lines also exposed with Au ions at 240 keV. Line widths are varied from 0.2 μm to 0.4 μm from left to right.

also found to be absent, and features down to 0.08 μm linewidth were exposed. Because of its high sensitivity and potentially fast writing speed, focused ion beam exposure combined with silylation may be preferable to the more commonly used electron beam lithography.

3.11 Focused Ion Beam Induced Deposition of Platinum

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Micrion
Contract M08774
U.S. Army Research Office
Contract DAAL03-87-K-0126

Project Staff

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Platinum has been deposited using a precursor gas of (methylcyclopentadienyl) trimethyl platinum and creating a local gas ambient using a capillary feed tube directed at the surface where the ion beam is incident. Pt is of interest for x-ray mask repair because it is a high density material. It also has advantages for integrated circuit repair since it is compatible with Si processing and has shown a relatively low resistivity. We have used Pt to rewire circuits by first milling contact vias through the passivation layer and then depositing a "jumper" of Pt to connect two metal lines. Since in circuit repair, and even more so in x-ray mask repair, deposition will need to be performed over existing topography, the deposition rate as a function of the angle of incidence is important. Accordingly, we have measured the deposition as a function of angle of incidence by scanning the ion beam across a glass fiber and measuring the thickness of the deposit at various angles using a scanning electron microscope (SEM). As expected, the deposition yield (number of atoms deposited/incident ion) increases sharply as grazing incidence is approached. See figure 2.

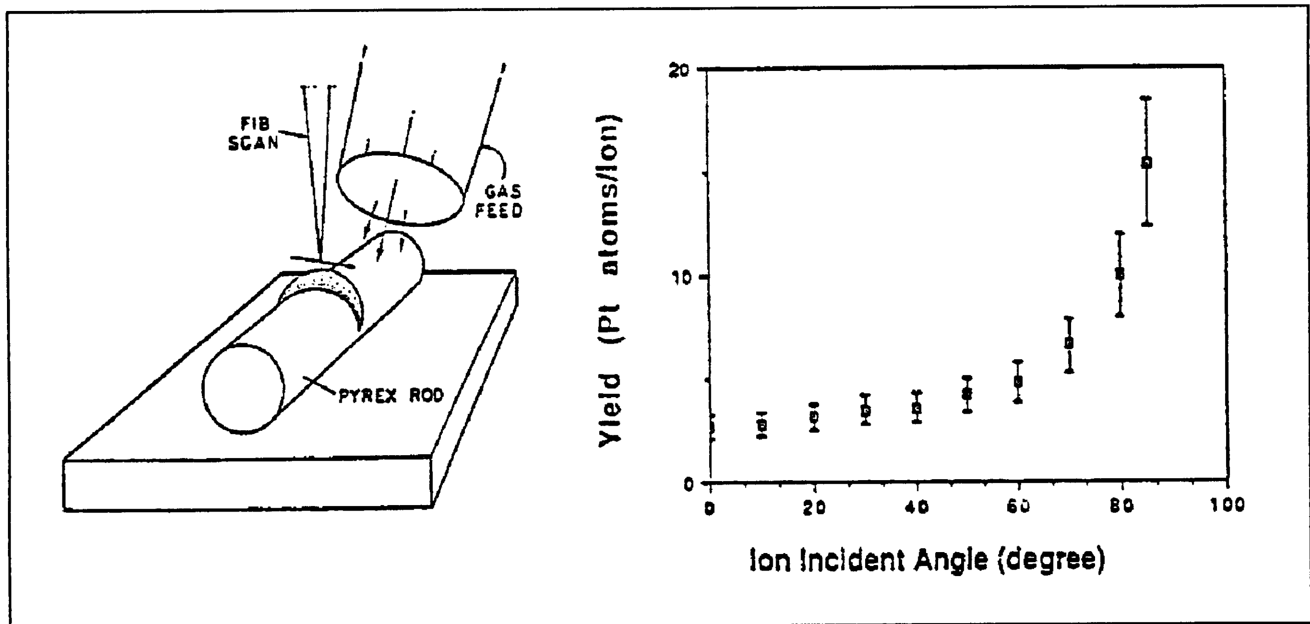

Figure 2. Measurement of focused ion beam deposition yield as a function of incidence angle. The results were obtained by depositing over a pyrex fiber 3 μm in diameter as shown schematically (on the left). The yield is found to increase as the angle of incidence approaches 90°. Incidentally the sputtering yield similarly increases as grazing incidence is approached.

3.12 Ion Induced Deposition of Gold, Results and Models for the 2 to 10 keV Energy Range

Sponsor

IBM Corporation

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Andrew D. Dubner, Dr. Alfred Wagner,[7] Professor Carl V. Thompson, Dr. John Melngailis

To study the mechanism of ion induced deposition, a UHV apparatus was constructed with a 2 to 10 kV ion source directed at a quartz crystal microbalance acting as the sample. The adsorption of the precursor gas, dimethylgold hexafluroracetylacetonate, the deposition rate of gold and the milling rate of gold could be measured accurately and quickly, *in-situ*. Data was taken for all of the noble gas ions from He to Xe at energies between 2 and 10 kV. Numerous observations pointed to the fact that the process by which adsorbed gas molecules are dissociated is substrate mediated. Two models of the process, the thermal spike and the collision cascade model, were analyzed and used to fit the observed data. In the thermal spike model, the instantaneous temperature rise surrounding the point of ion impact is calculated and assumed to cause the dissociation. In the Monte-Carlo collision-cascade model, the excitation of individual surface atoms is calculated and assumed to cause the dissociation. The collision-cascade model fits the observed data well and supports the view that this is the atomic process by which ion induced deposition occurs.

3.13 Ion Induced Deposition of Gold, Results and Models for the 50 to 100 keV Energy Range

Sponsors

Micrion
  Contract M08774
U.S. Army Research Office
  Contract DAAL03-87-K-0126

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The ion induced gold deposition yield and the sputter yield have been measured using a special gas cell apparatus constructed to fit in the endstation of an implanter. Noble gas ions were used. The film composition and microstructure

[7] IBM Corporation Research Division, Yorktown Heights, New York.

have been measured under various conditions. The heavier mass ions Kr to Xe yield films that are 80% Au and 20% carbon, while the lower mass ions yield films that are near 50-50. Preliminary calculations indicate that the differences of dissociation yield on ion mass and ion energy appears to fit the collision cascade model. In addition, the dissociation and sputter yield has been calculated as a function of ion incidence angle. The results appear to fit the observed increases in yield as grazing incidence is approached.

3.14 Publications

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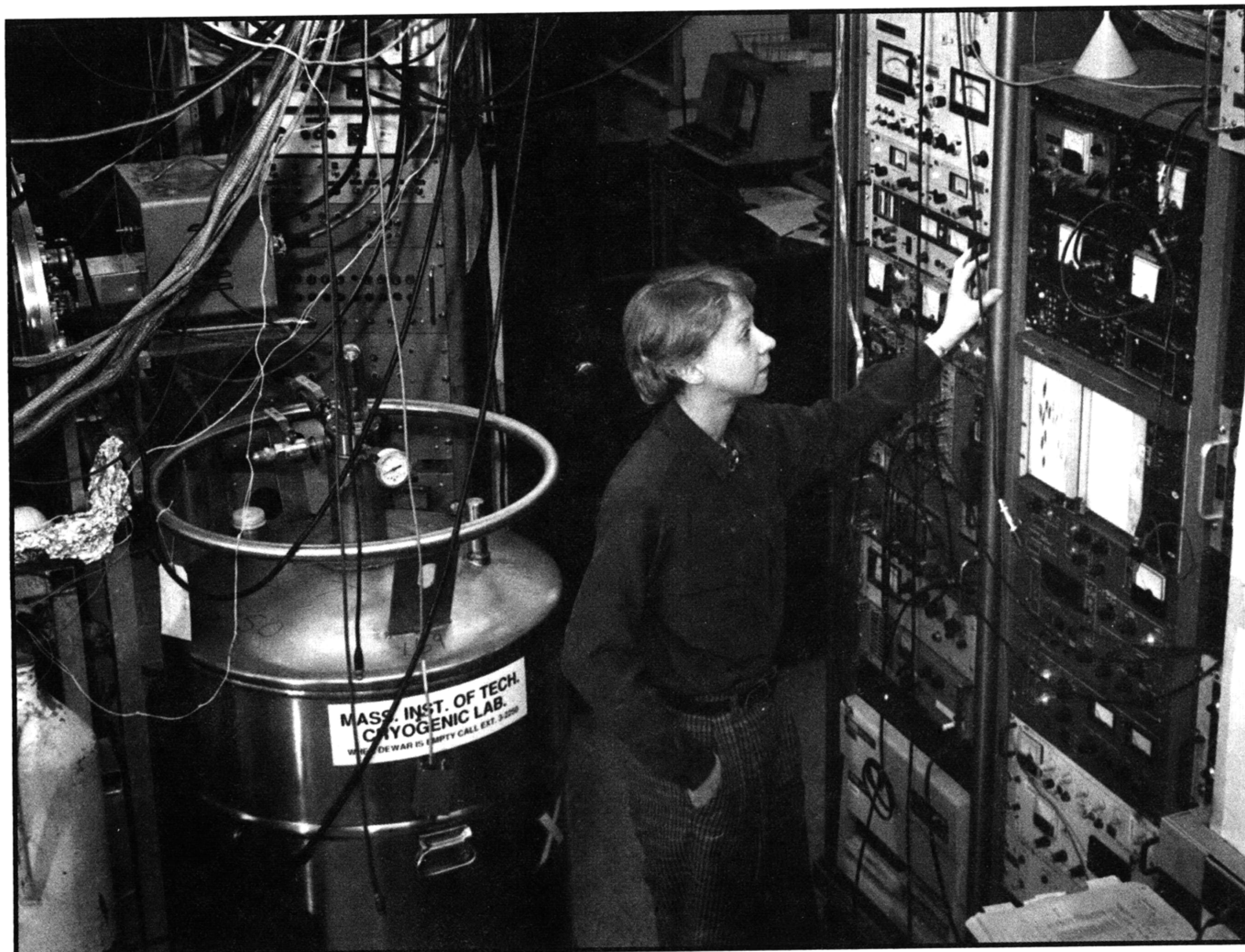

Professor Sylvia T. Ceyer conducts molecular beam surface scattering experiments in order to analyze the chemistry that occurs during the plasma etching of silicon and gallium arsenide.