

Chapter 6. Focused Ion Beam Microfabrication

Academic and Research Staff

Dr. John Melngailis, Professor Dimitri A. Antoniadis, Professor Carl V. Thompson, Dr. Xin Xu, Sergey Etchin, Mark I. Shepard

Visiting Scientists and Research Affiliates

Dr. Dominique Vignaud, Akira Shimase, Jane Sosonkina

Graduate Students

Tony P. Chiang, William Chu, Anthony D. Della Ratta, Henri J. Lezec, Kenneth S. Liao, Christian R. Musil, Jaesang Ro

Technical and Support Staff

Donna R. Martinez

6.1 Introduction

The focused ion beam research program at MIT can be divided into two areas. The first, served by a 150 kV system, is the high energy regime and includes implantation and lithography. The second is the lower energy regime and is aimed at developing repair processes for 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 $\pm 0.1 \mu\text{m}$ 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 on Si wafers partly fabricated at Ford Aerospace and on GaAs wafers fabricated at 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 $0.1 \mu\text{m}$ 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.

In the lower energy regime our work has mainly focused on the development of 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 $0.1 \mu\text{m}$. 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, on understanding the fundamentals of the process, and on deposition at non-normal incidence. Mainly Ga^+ ions in the range of 10-50 kV are used.

Our work in this area will be greatly enhanced by the recent donation of an FEI 500D focused ion beam system to MIT. This system is more convenient and flexible and compliments our existing, largely home-built machine. The FEI machine delivers Ga^+ ions at energies of 5 to 25 kV and beam diameters down to $0.05 \mu\text{m}$.

6.2 Tunable Gunn Diodes—High Frequency Performance and Applications

Sponsor

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

Project Staff

Henri J. Lezec, Christian R. Musil, Leonard J. Mahoney,¹ Dr. Alex Chu,² Larry Chu,³ Professor Dimitri A. Antoniadis, Dr. John Melngailis

Gunn diodes have been fabricated by focused-ion-beam implanting Si in the GaAs surface area between two contacts. This planar fabrication is easily incorporated into GaAs microwave integrated circuits. To achieve tunability the focused ion beam is programmed to implant a gradient of doping in the direction of current flow. This means that the frequency of oscillation of the Gunn diode depends on the bias resulting, in effect, in a voltage controlled oscillator (VCO). The maximum frequency of oscillation observed so far is 42 GHz with a tuning range of 20 GHz. The performance of two of these devices is shown in figure 1. These VCOs are expected to have numerous applications in high performance GaAs monolithic microwave integrated circuits (MMICs). The most immediate application is a built-in test where a swept frequency Gunn diode is coupled to the input, and a planar diode detector is coupled to the output of the device under test. This permits the RF performance to be tested by means of D.C. probes.

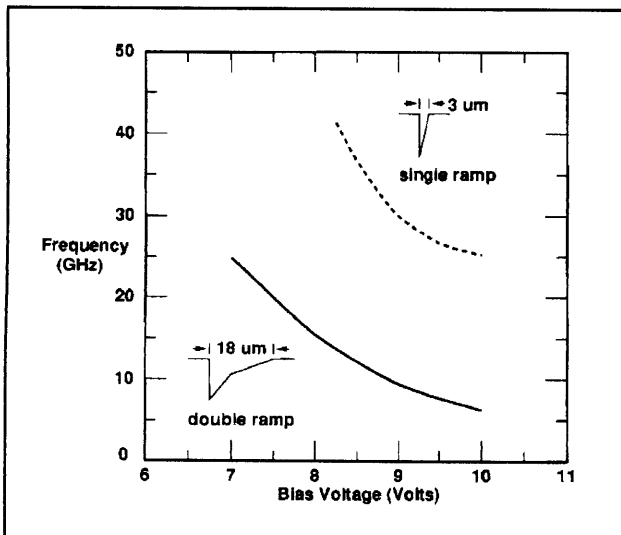


Figure 1. Measured frequency versus bias voltage for two Gunn diodes. The inserts show schematically the doping profiles, which are generated by ramping the implanted dose of Si ions from 0.5 to 1.5×10^{13} ions/cm².

¹ MIT Lincoln Laboratories.

² Mitre Corporation, Bedford, Massachusetts.

³ M/A Com Corporation, Burlington, Massachusetts.

6.3 Simulation of Tunable Gunn Diodes and MESFETs with Doping Gradients

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Project Staff

Christian R. Musil, Henri J. Lezec, Professor Dimitri A. Antoniadis, Dr. John Melngailis

The tunable Gunn diodes and MESFETs we have fabricated with focused ion beam gradients have complex carrier dynamics. The properties of these devices have been simulated on the Cray computer using a non-stationary hydrodynamic solution of the Boltzmann transport equation. In the MESFETs this permits visualization of the effects of doping gradients and the formation of stationary Gunn domains. In the case of the tunable Gunn diodes the bias-dependent domain propagation length, which in effect produces the tunability, is simulated. As shown in figure 2, a non-equilibrium carrier concentration is associated with the propagating Gunn domain. Each domain travels up the implanted carrier concentration gradient until a new domain is nucleated at the low carrier concentration end.

6.4 Limited Lateral Straggle of Focused-Ion-Beam Implants

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Project Staff

Dr. Dominique Vignaud, Kenneth S. Liao, Christian R. Musil, Akira Shimase, Professor James Chung, Sergey Etchin, Professor Dimitri A. Antoniadis, Dr. John Melngailis

The minimum lateral dimensions of focused ion beam implanted doping profiles is ultimately

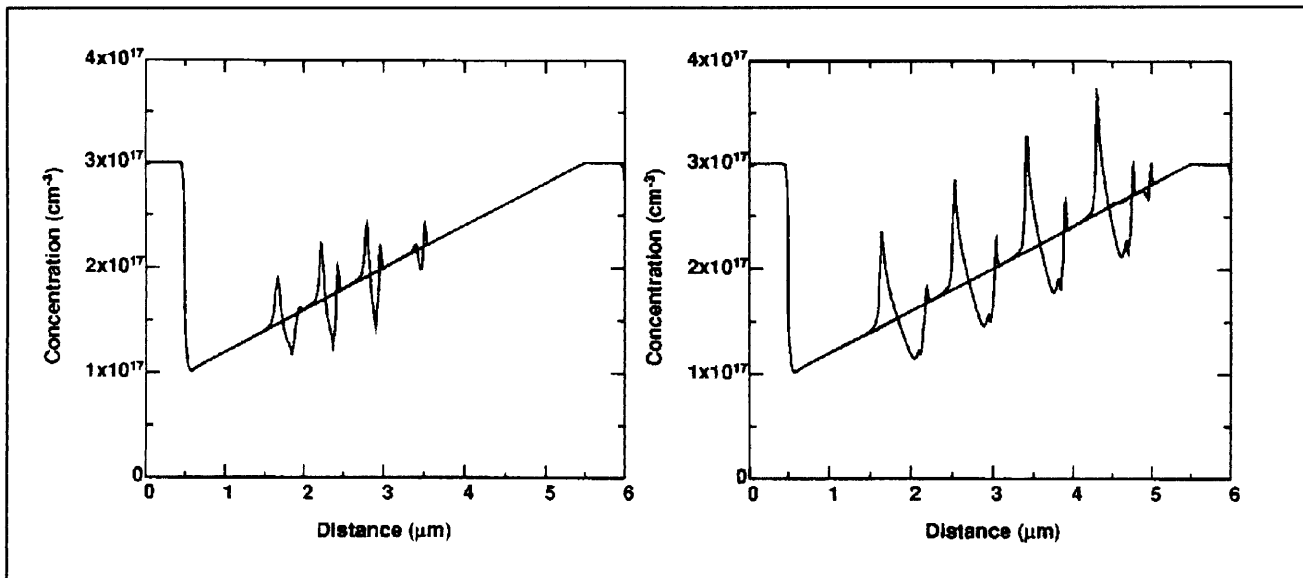


Figure 2. Simulated electron concentration profiles versus lateral position at successive time intervals during domain propagation. Left: bias = 2 V, frequency = 40 GHz, $\Delta t = 6$ psec. Right: bias = 6 V, frequency = 25 GHz, $\Delta t = 12$ psec.

limited by the lateral straggle of the ions as they penetrate into the crystal lattice. This is particularly true for light ions. One way to minimize the lateral straggle is to exploit channeling by implanting along a crystal axis. To verify this we have implanted Be in GaAs and B in Si both on-axis and off-axis. The focused ion beam was used to implant gratings of various periods. The extent of overlap between the grating lines was measured electrically. In GaAs two types of experiments were carried out. In the first a grating was implanted with lines parallel to the direction of current flow in an n-type mesa structure situated between two contacts. Since the implant was not annealed, insulating stripes were produced. As the period of the grating decreased the conduction was cut off. The results for 230 keV Be ions show that the lines begin to overlap at a period of 0.3 to 0.4 μm , but there is still a modulation of the conductivity down to below 0.1 μm for on-axis implants. In the second experiment, gratings were implanted in semiinsulating GaAs between two p-type contacts with the grating lines perpendicular to the current flow. These implants were rapid-thermal-annealed, and the conductivity sharply increased as the period decreased and the lines began to touch. Various doses were used between 3×10^{12} and 1×10^{14} ions/cm², and a clear difference was observed between on-axis and off-axis implants. The standard deviation of the lateral spread of the carriers was deduced from a one-dimensional model. The minimum half-

width of an implanted line was found to be 140 nm in on-axis material. In off-axis material the width was 50 to 90 nm larger depending on dose. In all cases the width is smaller than the 450 nm straggle predicted by Monte-Carlo simulations in amorphous material. Similar structures have also been made by implants in Si, but results are not yet available.

6.5 Focused Ion Beam Implantation of GaAs MMICs and Transistor Optimization

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Sergey Etchin, Dr. John Melngailis in collaboration with Dr. Thomas Kazior⁴

Some GaAs monolithic microwave integrated circuits (MMICs) require as many as five implantation steps in order to produce highly optimized transistors for various functions. Yet the area implanted in each step is small. The focused ion beam provides a potentially cost effective means of carrying out all five implants in a single fabrication step, thereby eliminating a large number of con-

⁴ Raytheon Corporation, Lexington, Massachusetts.

ventional steps: resist spinning, lithography, development, blanket implantation, and resist stripping, each repeated five times. Device patterns have been transferred from Raytheon to MIT and aligned local implants of MMICs have been carried out to verify that the performance of the focused ion beam implanted devices is equivalent to the the conventionally fabricated devices.

In addition, the capability of the focused ion beam to implant devices side by side each with a different dose or at a different ion energy has been used to optimize the performance of buried p-layer, n-channel MESFETs. In one experiment, for example, devices were implanted with Be ions at energies of 70, 90, and 110 keV and doses from 4×10^{11} to 1.5×10^{12} in order to find the optimum set of parameters. In another experiment, the Si-channel implant was also carried out with the focused ion beam, and the dose was varied from device to device. These successful experiments demonstrate the utility of the focused ion beam for device optimization. Similar optimization by conventional broad beam implantation would require many more wafers and would introduce complications due to wafer-to-wafer variations.

6.6 Ion Induced Deposition of Gold, Models and Microstructure

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Jaesang Ro, Professor Carl V. Thompson, Dr. John Melngailis

When a local gas ambient of, for example, an organometallic gas is created on a substrate, incident energetic ions can cause the adsorbed gas molecules to dissociate, creating a metallic deposit. With a focused ion beam, this technique can be used to write patterns of minimum dimensions down to $0.1 \mu\text{m}$. The technique is being used commercially for the local repair of integrated circuits. First, the ion beam is used to mill vias through the passivation, and then gas is introduced locally with a capillary gas feed and a metal "jumper" is connected between the vias. Deposi-

tion of metals, particularly high Z metals such as Au and W, is also being developed for the repair of x-ray lithography masks.

We have studied the microstructure of the gold film and the correlation between its microstructure and deposition conditions. Some carbon is always incorporated into the gold films. Three types of microstructures have been identified: (1) granules of gold in a carbon background produced at high ion current densities at room temperature, (2) columns of gold in a carbon background produced at lower current densities or at higher current densities on substrates at 100°C , and (3) polycrystalline gold with minimal carbon content produced at lower current densities in substrates at 100°C . For x-ray mask repair the granular or columnar structures are not desirable.

The deposition yield was also measured for all of the noble gas ions at energies of 50 and 100 keV. The deposition yield varied from 3 to 29 and was highest for the highest mass ion, Xe. A model of the process based on the Monte Carlo calculation of collision cascades fits the data. The collision cascades that terminate on the surface transfer energy to the adsorbed monolayer of organometallic gas molecules and cause dissociation.

6.7 Focused Ion Beam Lithography for X-Ray Mask Making

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Tony P. Chiang, Sergey Etchin, W. Chu, Professor Henry I. Smith, Dr. John Melngailis, in collaboration with Mark A. Hartney⁵ and D.C. Shaver⁵

One of the main challenges in the application of x-ray lithography is the making of the mask. The absorber material on the thin mask membrane must be fabricated of high Z material (e.g., Au or W) with high aspect ratio, (e.g., 0.25 to $0.5 \mu\text{m}$ thick at minimum dimensions down to $0.1 \mu\text{m}$). Two techniques for writing the original pattern of the mask in resist are electron beam lithography and focused ion beam lithography. While electron beams have been extensively developed and applied, ion beams have been used to write patterns down to $0.015 \mu\text{m}$ minimum linewidth and show no proximity effects even for resists over

⁵ MIT Lincoln Laboratory.

high Z material. The resist exposure times for the two techniques are comparable. Previously we have fabricated x-ray masks at MIT with minimum linewidth of $0.05\ \mu\text{m}$. The goal of this program is to fabricate x-ray masks for use at the Center for X-Ray Lithography at the University of Wisconsin. Masks will be made initially by exposing PMMA and plating up the gold absorber. An alternate process which may be preferable for the making of x-ray masks with a tungsten absorber is focused ion beam exposure followed by resist silylation. We have demonstrated this silylation process in collaboration with Lincoln Laboratory and have achieved minimum dimensions of $0.08\ \mu\text{m}$ in $1\ \mu\text{m}$ thick resist. The writing in this process is as fast as the fastest e-beam. In addition, the resist used is compatible with reactive ion etching. Thus, we will pursue making x-ray masks using reactive ion etching to define the high aspect ratio patterns in tungsten.

6.8 Focused Ion Beams for the Repair of X-Ray Masks

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U.S. Navy - Naval Research Laboratory/Micrion Agreement M08774

Project Staff

Dr. Xin Xu, Anthony D. Della Ratta, Jane Sosonkina, Dr. John Melngailis

X-ray lithography is being developed for the fabrication of integrated circuits with minimum dimensions of $0.25\ \mu\text{m}$ and below. The masks needed for this lithography will have over 10^9 features. Thus it is unlikely that they will be fabricated free of defects. The focused ion beam is the logical tool for the local repair of mask defects and is being developed for this purpose. Local ion milling can be used to remove unwanted absorber and ion induced deposition can be used to add missing absorber. The challenge is that these structures must be refabricated with high aspect ratios often in the proximity of existing high aspect ratio structures. Thus, ion milling and ion induced depositions at non-normal incidence is unavoidable. We have measured the ion induced deposition of gold as a function of the angle of incidence. The precursor gas used was dimethyl-gold hexafluoro-acetylacetonate. The deposition yield was found to rise rapidly as the angle of incidence approaches a grazing angle. In addition, at angles above about 50° (0° is normal, 90° is grazing) the deposited structure takes on a ripply, irregular aspect which develops into an almost periodic array of protrusions at grazing incidence.

We are also measuring the milling yield as function of the angle of incidence. Both of these aspects of the repair process need to be taken into account if high aspect ratio mask structures are to be accurately refabricated.

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