

1. Submicron Structures Technology and Research

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1.1 Submicron Structures Laboratory

The Submicron Structures Laboratory at M.I.T. develops techniques for fabricating surface structures of nanometer to micrometer linewidths and uses these structures in a variety of research projects. This laboratory contributes to a major expansion of research at M.I.T. in microsystems and electronic materials. The research projects of the laboratory, which are described briefly below, fall into four major categories: submicron structures fabrication techniques (no. 2); submicrometer electronics (nos. 3 to 6); crystalline films on amorphous substrates (nos. 7 to 9); periodic structures and applications (nos. 10 to 13).

1.2 Microfabrication at Linewidths of 0.1 μm and Below

Joint Services Electronics Program (Contract DAAG29-83-K-0003)

U.S. Navy - Office of Naval Research (Contract N00014-79-C-0908)

National Science Foundation (Grant ECS82-05701)

Erik H. Anderson, Irving Plotnik, Mark L. Schattenburg¹, John Melngailis, Henry I. Smith

A variety of process techniques for fabricating structures with characteristic dimensions of 0.1 μm and below are under development. These include: conventional holographic lithography, achromatic holographic lithography, x-ray lithography, and reactive-ion etching. A "thick photoresist" technique in conjunction with conventional holographic lithography has been used to produce structures which would otherwise require many extra process steps. Achromatic holographic configurations have been investigated in order to use deep UV excimer laser sources to produce gratings with even finer periods ($<0.1 \mu\text{m}$) than are possible with conventional UV laser sources. Although such optical techniques can be used to prepare experimental samples, there are important advantages to using x-ray lithography for this purpose. With C_K x-ray lithography

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details on the mask $\sim 100 \text{ \AA}$ are replicated. A new, "all dry", process has been developed to fabricate high-contrast masks for x-ray lithography. This process uses tungsten as the absorber material and reactive-ion etching with CBrF_3 to transfer the pattern into the tungsten film. High-aspect-ratio (almost 8:1) structures with linewidths as small as 450 \AA have been produced in PMMA using these new masks. These masks can be used to produce x-ray spectroscopy gratings, samples for graphoepitaxy experiments, and other microstructures.

1.3 Electronic Conduction in Ultra-Narrow Silicon Inversion Layers

Joint Services Electronics Program (Contract DAAG29-K-0003)

Robert F. Kwasnick, Jerome C. Licini, Marc A. Kastner, John Melngailis, Patrick A. Lee

The conductance of metal-oxide-semiconductor field effect transistors with $\sim 70 \text{ nm}$ wide and $7 \text{ }\mu\text{m}$ long inversion layers has been studied. At temperatures below 15 K strong non-monotonic fluctuations in conductance are observed as a function of electron density which is controlled by the gate voltage. Near threshold these fluctuations in source-to-drain conductance can be as high as 2 or 3 orders of magnitude. Studies of this phenomenon as a function of temperature and drain voltage indicate that spatial barriers, which contain tunneling channels, exist in the narrow inversion layers. New structures have been fabricated with more uniform 70 nm -wide gate structures using tungsten films instead of aluminum. The measurements are also being extended to temperatures in the milli-kelvin range.

1.4 Corrugated Gate MOS Structures

Joint Services Electronics Program (Contract DAAG29-83-K-0003)

Alan C. Warren, Dimitri A. Antoniadis, John Melngailis, Henry I. Smith

The principle goal of this work is to demonstrate and understand the effects of a periodic or a confining potential on electrons in silicon inversion layers where critical lateral dimensions are comparable to inelastic scattering lengths. Toward this goal, MOS transistors have been fabricated with a periodic, dual-stacked-gate structure composed of a lower tungsten grating electrode embedded in SiO_2 , and an independent upper electrode consisting of an aluminum pad. The 200-nm -period grating gate was fabricated on a thermally grown, 30 nm -thick oxide using x-lithography and lift-off. The grating was subsequently covered with 200 nm of CVD oxide which separated it from the upper gate electrode. Devices with grating lines oriented perpendicular to the current flow produce a weak, periodic potential in the inversion layer with which superlattice effects may be observed when the inelastic scattering length exceeds the grating period. The longitudinal grating orientation, with ~ 250 quasi-1-D channels in parallel, can be used to explore

quantum effects in ultra-narrow inversion layers. Preliminary measurements at liquid He temperatures reveal regular large-scale structure in the conductance which corresponds to that expected when the density-of-states has been altered either through a weak, periodic potential (perpendicular orientation), or through a 2-D confining potential (longitudinal orientation).

1.5 Submicron FET's in Si

Joint Services Electronics Program (Contract DAAG29-83-K-0003)

Stephen Y. Chou, Dimitri A. Antoniadis, Henry I. Smith, John Melngailis

A novel technique for making x-ray masks has been developed that enables exposure on the same substrate of resist patterns corresponding to channel lengths in the range $\sim 500 \text{ \AA}$ to $5 \mu\text{m}$ without the need for electron beam lithography. The mask has the narrow absorber lines on the front side and the coarse patterns on the back side. Rectangular wells with vertical (111) sidewalls are etched anisotropically in (110) Si, and then this relief structure is transferred to polyimide by molding. The front-side gold lines are formed by oblique evaporation while the back-side absorber patterns are formed using conventional photolithography and ion etching. Using this mask together with C_K x-ray replication, As ion implantation and conventional MOS processing, we fabricated transistors with minimum channel length in the range 750 \AA to $5 \mu\text{m}$. In the future, the characteristics of these devices will be compared with predictions based on device-scaling models.

1.6 Submicron-Gap High-Mobility Silicon Picosecond Photodetectors

Joint Services Electronics Program (Contract DAAG29-83-K-0003)

Ghavam G. Shahidi, Erich P. Ippen, John Melngailis

Submicron dimension gaps in an Al stripline were fabricated on a silicon-on-sapphire substrate. The gaps were fabricated by creating a sharp step on the silicon by reactive-ion etching and then shadow evaporating Al at a 45° angle. The shadow of the step defines the gap. With these structures high speed photoconductive switching in silicon is achieved, without a reduction in mobility or lifetime, by carrier sweep-out. Using photoconductive gaps ranging in width from $14 \mu\text{m}$ to $0.22 \mu\text{m}$, we have studied the variation of switching speed with gap dimension and applied voltage. With submicron gaps and optical energies of less than a nanojoule, we have been able to switch pulses of more than 1 volt with durations as short as 27 psec FWHM.

1.7 Graphoepitaxy of Si, Ge, and Model Materials

National Science Foundation (Grant ECS82-05701)

U.S. Navy - Office of Naval Research (Contract N00014-79-C-0908)

Semiconductor Research Corporation (Grant 83-01-033)

Joyce E. Palmer, Chee C. Wong, Takao Yonehara, Stephen M. Garrison, Harry A. Atwater, Carl V. Thompson, Henry I. Smith

Graphoepitaxy, in which an overlayer film is crystallographically oriented by an artificial surface pattern, was demonstrated several years ago. However, to achieve single-crystal films on a variety of substrates for electronic and optical devices the crystallographic quality of films must be improved significantly, and low-temperature processes must be employed. This, in turn, demands improved understanding of the fundamental mechanisms of grain growth and reorientation in contact with artificial surface patterns. Current theory indicates that the optimal approach to graphoepitaxy is to use ultrathin ($\sim 300 \text{ \AA}$) films over the finest patterns available (linewidth $< 1000 \text{ \AA}$) and to induce surface-energy-driven secondary grain growth. In pursuit of this approach we conduct basic studies of secondary grain growth and graphoepitaxy in Si, Ge and model materials such as Sn and Au. (The latter two are chosen because they exhibit large interfacial anisotropies and high grain-boundary mobility.) Theoretical models for surface-energy-driven secondary grain growth were developed and have been confirmed, in part, by experiments on Si. In the studies of Sn we found that the low-temperature tetrahedrally-bonded α phase is retained up to and beyond room temperature in films $\sim 300 \text{ \AA}$ thick. In films of Ge 300 \AA thick we achieved graphoepitaxial orientation by the purely solid-state, surface-energy-driven process. Emphasis in the future will be on further basic studies, understanding the role of film stress and controlling its effects, and developing new means of selectively enhancing grain boundary mobility.

1.8 Zone-Melting Recrystallization of Si for Solar Cells

U.S. Department of Energy (Contract DE-AC02-82-ER-13019)

Harry A. Atwater, Henry I. Smith, Carl V. Thompson

Zone melting recrystallization (ZMR) of Si of SiO_2 , a process which has produced high quality crystalline films with (100) texture, is being investigated to produce low-cost solar cells. A transparent substrate coated with a diffusion barrier would serve as the window for the cell module. Cells have been fabricated with single-side interdigitated contacts in $60 \mu\text{m}$ -thick Si films. Spectral response measurements indicate a carrier diffusion length of $50 \mu\text{m}$, with a long-wavelength response similar to that seen in much thicker cells. The good long-wavelength response is a result of the enhancement of the effective optical thickness due to the naturally faceted texture in our films. Cells of 7% efficiency were produced. The limit to the cell efficiency

is believed to be junction and contact fabrication problems.

1.9 Integration of Si and III–V Materials

U.S. Department of Energy (Contract DE-AC02-82-ER-13019)

Stephen C. Schott, Harry A. Atwater, Carl V. Thompson, Henry I. Smith

The success of Si zone-melting recrystallization (ZMR) in producing device-quality films has prompted us to investigate if similar results can be achieved with the III–V materials. These materials present special problems of adhesion, stoichiometry control, and differential vapor pressure at the melting point. Initial efforts have used InSb, which was deposited by flash evaporation. These experiments were partially successful but point out the difficulties of zone melting binary compounds. A more promising short-term approach is to develop a zone-melting technology for Ge, upon which GaAs can be grown epitaxially. Germanium is more difficult to zone melt than Si because of its poor adhesion to SiO₂. Current experiments involve fully encapsulating islands of Ge with combinations of SiO₂ and SiO.

1.10 Submicrometer-Period Gold Transmission Gratings for X-Ray Spectroscopy

Lawrence Livermore National Laboratory (Contract 2069209)

Joint Services Electronics Program (Contract DAAG29-83-K-0003)

Mark L. Schattenburg¹, Erik H. Anderson, Irving Plotnik, Henry I. Smith

Gold transmission gratings with periods of 0.2 and 0.3 μm and thicknesses ranging from 0.5 to 1 μm are fabricated using a combination of holographic lithography, x-ray lithography, and electroplating. These gratings are either supported on polyimide membranes or are made self-supporting by the addition of crossing struts. They are used for spectroscopy of the x-ray emission from plasmas produced by high-power lasers. Gratings fabricated in our lab by these techniques have been used in key diagnostic instruments associated with the first reported soft x-ray laser developed at Lawrence Livermore Laboratory.

1.11 High-Dispersion, High-Efficiency Transmission Gratings for Astrophysical X-Ray Spectroscopy

National Aeronautics and Space Administration (Contract NAS5-27591)

Mark L. Schattenburg¹, Claude R. Canizares¹, Henry I. Smith

Gold gratings with spatial periods of 0.1 – 10 μm make excellent dispersers for high resolution

x-ray spectroscopy of astrophysical sources in the 100 eV to 10 KeV band. These gratings are planned for use in the Advanced X-ray Astrophysics Facility (AXAF) which will be launched in the early 1990's. In the region above 3 KeV, the requirements of high dispersion and high efficiency dictate the use of the finest period gratings with aspect ratios approaching 10:1. To achieve this we first expose a grating pattern in 1.5 μm -thick PMMA over a gold plating base using Carbon-K x-ray lithography. To date, we have worked with gratings having periods of 0.3 or 0.2 μm (linewidth 0.15 – 0.1 μm). Gold is then electroplated into the spaces of the PMMA to a thickness of 1 μm .

1.12 A Display Based on Switchable Zero Order Diffraction Grating Light Valves

Defense Advanced Research Projects Agency (Contract N00014-79-C-0908)

Josephine A. Stein, Deborah A. Summa, John Melngailis, Jan A. Rajchman², Henry M. Paynter

A flat-panel display technology has been conceived and is being developed which utilizes a matrix of line-addressable light valves back lighted with a partially collimated source. The basic pixel element of the display is an optical switch based on the zero order of diffraction by two facing aligned transmission phase gratings. The transmission of light is modulated by mechanically displacing one grating with respect to the other by one-half of the grating period. The color transmitted by the light valve is controlled by the grating profile.

Optical spectra of a large-scale prototype of the switchable light valve element are in good agreement with calculations according to simple diffraction theory. Technology for the construction of an optical switch of the desired size has been developed, with 85% of the area devoted to light transmission. The elements are one millimeter squares made of polyvinylidene fluoride (PVDF), a transparent, piezoelectric plastic. Gratings of nearly square-wave profile with 3.8 micron period and depths from 0.6 to 1.8 microns are produced in 9 micron films of PVDF by embossing at 4000 bars and 70°C and show the expected optical transmission spectra. Mechanical displacement is produced by applying voltage to two sets of bending arms attached to either side of the movable element. The bending arms amplify motion due to piezoelectric strain. Nickel electrodes are patterned onto the PVDF film by photolithography and liftoff. Perforations around the movable element and the bending arms are etched through the film by reactive ion etching in oxygen, using patterned aluminum as a mask. Motion exceeding 2 microns has been observed, which is sufficient to operate the light valve.

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1.13 Studies of Surface Acoustic Wave Propagation in Gratings

National Science Foundation (Grant ECS80-17705)

Dong-Pei Chen, Hermann A. Haus, John Melngailis

The reflection of surface acoustic waves from normal incidence metal overlay gratings has been calculated using the coupling of modes formalism. The reflection is due to field shorting and to mass loading. Under special circumstances these two effects can be made to cancel. This result may be of importance in the design of surface acoustic wave transducers where reflection is an unwanted effect. Gratings in gold of various thicknesses and of various line-to-space ratios have been fabricated on LiNbO_3 , and the reflection coefficients have been measured. The reflection coefficient decreases as a function metal linewidth in qualitative agreement with theory. The phase of the reflected wave is also observed to reverse as a function of linewidth near the point where the reflectivity is expected to go through zero.

1.14 Near IR Grating Polarizers

National Aeronautics and Space Administration (Contract NGL22-009-638)

Erik H. Anderson, Irving Plotnik, Mark L. Schattenburg¹, Henry I. Smith

Very-fine-period grating structures are effective optical polarizing elements. New process procedures have been developed to fabricate a near-IR grating polarizer-beam splitter for use in a satellite instrument, the Diffuse Infrared Background Explorer. These structures have the highest reported performance in the wavelength region of interest (0.9 – 5 μm) of polarizers that can tolerate temperature cycling to 2°K, the instrument operating temperature. Prototype grating-polarizers have been fabricated and are being tested at NASA.

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