

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 with linewidths in the nanometer to micrometer range, 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: microfabrication techniques (no. 2); submicrometer electronics (nos. 3 to 5); crystalline films on amorphous substrates (no. 6); periodic structures and applications (nos. 7 to 10).

1.2 Microfabrication at Linewidths of 0.1 μm and Below

Joint Services Electronics Program (Contracts DAAG29-83-K-0003 and DAAL03-86-K-0002)

National Science Foundation (Grants ECS82-05701 and ECS85-06565)

Lawrence Livermore Laboratory (Subcontract 2069209)

Erik H. Anderson, William Chu, Irving Plotnik, Mark L. Schattenburg, Henry I. Smith, Anthony Yen

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. Achromatic holographic configurations may enable us to use deep UV excimer laser sources to produce gratings with 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 them only for preparing x-rays masks. These masks are then replicated using x-ray lithography. With C_K and Cu_L x-ray lithography high-aspect-ratio (almost 8:1) structures with linewidths as small as 450 \AA have been produced in PMMA.

An analysis of the combined effects of diffraction, penumbra and photoelectron range in x-ray lithography has shown that for replication of 500 \AA feature sizes the wavelength must be $\sim 10 \text{ \AA}$, and the mask-to-sample gap must be in the range $1\text{--}3 \mu\text{m}$.

A statistical analysis of the lithographic process was carried out which enables one to compare the efficacy of various lithographic techniques and evaluate the impact of resist speed and contrast on linewidth control.

1.3 Corrugated Gate MOS Structures

Joint Services Electronics Program (Contracts DAAG29-83-K-0003 and DAAL03-86-K-0002)
Alan C. Warren, Dimitri A. Antoniadis, Henry I. Smith, Terry Orlando, John Melngailis

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. MOS transistors were 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-ray lithography and lift-off. The grating was subsequently covered with 200 nm of CVD oxide which separated it from the upper gate electrode. In devices with grating lines oriented perpendicular to the current flow the periodic modulation of the inversion layer potential produced a modulation of the source-drain conductance at temperatures below 4.2 K . This confirmed earlier speculation that the lateral-surface-superlattice effect could be observed if the grating period was larger than the elastic scattering length, but smaller than the inelastic scattering length, (the electron loses coherence only in an inelastic event). In devices with a longitudinal grating orientation, with ~ 250 quasi-1-D channels in parallel, quantum effects in ultra-narrow inversion layers were explored. At 1.2 K , a weak modulation of the transconductance was observed and attributed to a modulation of the momentum relaxation time as the fermi level was raised, enabling higher level lateral modes to be excited.

1.4 MOSFET's in Si with Deep-Submicron Channel Lengths

Joint Services Electronics Program (Contracts DAAG29-83-K-0003 and DAAL03-86-K-0002)
Stephen Y. Chou, Dimitri A. Antoniadis, Henry I. Smith, Ghavam G. Shahidi

The electronic conduction in sub-100-nm channel length, Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET's) in Si has been studied. The sub-100-nm channel MOSFET's were fabricated with a combination of x-ray and optical lithographies. The x-ray mask, which defined the minimum lithography features, was fabricated with conventional photolithography, anisotropic etching and oblique shadowing. The gate oxide thickness, the channel doping concentration and the junction depth of the devices were properly scaled down, according to an empirical rule, for achieving quasi-long-channel behavior in sub-100-nm channel length MOSFET's.

The minimum channel length achieved in an operating MOSFET was 60 nm. At room temperature, MOSFET's with a channel length of 75 nm or longer showed well behaved quasi-long-channel I-V characteristics, and high transconductance. At 4.2 K, in the devices of 75 nm channel length, the velocity overshoot phenomenon was observed for the first time. Magnetic quantum effects were studied as well. We have observed, for the first time, that the Shubnikov-de Haas (SdH) peaks corresponding to the higher cyclotron orbits disappeared as the channel length was reduced to the sub-100-nm range. The SdH effect was used to characterize the length of the flat part of the channel potential, and to determine the real gate-channel capacitance of the deep-submicron devices.

We have modified the design of the devices to achieve higher mobility and smaller source and drain resistances. We expect to see higher transconductances and velocity overshoot at temperatures above 4.2 K.

1.5 Studies of Electronic Conduction in Submicron Silicon Inversion Layers

Joint Services Electronics Program (Contracts DAAG29-83-K-0003 and DAAL03-86-K-0002)

National Science Foundation (Grant ECS85-03443)

Jerome C. Licini, John Scott-Thomas, Samuel L. Park, Marc A. Kastner, John Melngailis, Dimitri A. Antoniadis, Henry I. Smith

Field effect transistors have been fabricated in Si with widths as narrow as ~50 nm. The narrow gate of these MOSFET's is created by glancing-angle evaporation of tungsten onto a 50 nm high step etched in a 100 nm oxide on a Si (100) surface. The tungsten wires are more uniform than those fabricated previously of Al, presumably because of the smaller grain size. More recently, work on a new design has begun in which the inversion layer is created under a narrow slot in a wide metal gate by applying a potential to an upper metal gate separated from the first by a layer of SiO₂.

During the past year attention was focused on the regime of gate voltage V_G well above

threshold, in which the fluctuations of conductance with V_G are much smaller. In experiments carried out in collaboration with D.J. Bishop of AT&T Bell Laboratories, we measured the magnetoresistance of our MOSFET's at ultralow temperatures and discovered aperiodic magnetoresistance oscillations similar to those seen previously in ultranarrow metal wires and narrow strips of GaAs. The oscillations in magnetoresistance remain unchanged for small changes in V_G below a critical value and become uncorrelated for changes in V_G larger than this value. This provides strong evidence that the oscillations do not result from energy shifts of electronic states but rather from field-induced changes in the phase of the wavefunctions. We believe that the fluctuations in resistance with V_G and magnetic field are an example of the quantum-interference effect predicted for all disordered conductors by P.A. Lee and A.D. Stone.

These experiments have provided another example of the importance of ultralow temperature measurements in understanding quantum mechanical transport phenomena in submicron structures. In order to carry out such experiments at M.I.T. we have ordered a dilution refrigerator and 10 T superconducting magnet from Oxford Instruments.

1.6 Crystalline Films on Amorphous Substrates

National Science Foundation (Grants ECS82-05701 and ECS85-06565)

U.S. Air Force - Office of Scientific Research (Grant AFOSR-85-0154)

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

The development of methods for producing crystalline films on amorphous substrates is an important aspect of our program. This is motivated by the belief that the integration of future electronic and electrooptical systems will be facilitated by an ability to combine, on the same substrate, a broad range of materials (Si, III-V's, piezoelectrics, light guides, etc.). Zone melting recrystallization (ZMR) has been highly successful but device-quality films are obtained only at the expense of high processing temperatures since the material of interest must be melted. ZMR has been an important testing ground for materials combinations, and for a number of novel concepts based on the use of lithography to control in-plane orientation and the location of defects.

The most promising approach in the long-term to crystalline films on amorphous substrates is, in our view, based on surface-energy-driven secondary grain growth (SEDSGG). In this approach, no melting or phase change occurs. Instead, we take advantage of the very large surface energies inherent in ultra-thin ($\sim 200 \text{ \AA}$) films to drive the growth of large secondary grains having specific crystallographic planes parallel to the surface. This phenomenon has been demonstrated, as has the use of very fine gratings ($\sim 1000 \text{ \AA}$ linewidths) to control the in-plane orientation (i.e., graphoepitaxy in combination with SEDSGG). Currently, research is focused on

basic studies of grain growth phenomena in ultra-thin films and means for promoting grain growth at temperatures many hundreds of degrees below the melting point. Theoretical models for surface-energy-driven secondary grain growth were developed and have, for the most part, been confirmed by experiments on Si, Ge, and Au films. Both ion bombardment and intense optical irradiation enhance grain boundary mobility. In the case of Ge thin films, self implantation at 500° C with 30 keV Ge ions achieves a grain growth that by thermal annealing would require 775° C. In thin films of gold, secondary grain growth occurs at room temperature as soon as the film becomes continuous (at $\sim 175 \text{ \AA}$). Low energy Ar ion bombardment enhances grain-boundary mobility in Au. In films of Ge 300 Å thick we achieved graphoepitaxial orientation by the purely solid-state, surface-energy-driven process. If our basic studies prove fruitful we may be able to develop a low temperature method, applicable to all crystalline film materials, for producing device-quality films on amorphous substrates. By means of lithography, defects in the films, such as dislocations and stacking faults, would be localized at predetermined positions out of the way of devices.

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

Joint Services Electronic Program (Contracts DAAG29-83-K-0003 and DAAL03-86-K-0002)

Lawrence Livermore Laboratory (Subcontract 2069209)

Erik H. Anderson, Irving Plotnik, Mark L. Schatzenburg, 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 laboratory by these techniques have been used in key diagnostic instruments associated with the first reported soft x-ray laser developed at Lawrence Livermore Laboratory.

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

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

Mark L. Schatzenburg, Claude C. Canizaares, 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 10KeV 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. To achieve these we expose patterns 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 .

1.9 Soft X-Ray Interferometer Gratings

National Science Foundation (through KMS Fusion, Inc.)

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

In the soft x-ray region of the electromagnetic spectrum, reliable optical constant data is scarce or non-existent. In order to fill this gap, an achromatic interferometer instrument is under construction at KMS Fusion, Inc. The critical optical components of this instrument are a set of matched, 200 nm period, gold transmission gratings which are being fabricated at M.I.T. Because these gratings are used in an interferometer, the phase-front quality must be extremely good and at the same time the gold lines must be free-standing, i.e., have no support structure which would attenuate the x-rays.

1.10 Switchable Zero Order Diffraction Grating Light Valves

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

Josephine A. Stein, Deborah A. Summa, John Melngailis, Henry M. Paynter, Jan A. Rajchman, Ming K. Tse

A light valve based on the switching of the zero order of diffraction of a pair of aligned phase gratings has been conceived and demonstrated. The two gratings are embossed into surfaces of polyvinylidene fluoride PVF₂ which is a transparent piezoelectric plastic. The gratings are aligned face-to-face and a chevron structure with metal film contacts is fabricated on the periphery. A voltage applied to the electrodes causes displacement of the gratings and a switching from light blocking to light transmission. The chevron structure amplifies the motion; 2 μm displacement of the gratings has been observed. Methods of fabricating a flat-panel, back-lighted display using an array of such light valves have been examined. Although many of our fabrication steps for a single light valve, such as embossing, are consistent with mass production of a display, the assembly and alignment of the gratings proved to be quite difficult, and not easily adaptable to production.

Journal Articles

- Schattenburg, M.L., I. Plotnik, and H.I. Smith, "Reactive-Ion Etching of 0.2 μm Period Gratings in Tungsten and Molybdenum Using CBrF_3 ," *J. Vac. Sci. Technol. B* **3**, 272 (1985).
- Warren, A.C., D.A. Antoniadis, H.I. Smith, and J. Melngailis, "Surface Superlattice Formation in Silicon Inversion Layers Using 0.2 μm - Period Grating Electrodes," *IEEE Elect. Dev. Lett. EDL-6*, 294 (1985).
- Shahidi, G.G., E.P. Ippen, and J. Melngailis, "Submicron-Gap High-Mobility Silicon Picosecond Photodectors," *Appl. Phys. Lett.* **46**, 719 (1985).
- Thompson, C.V., "Secondary Grain Growth in Thin Films of Semiconductors: Theoretical Aspects," *J. Appl. Phys.* **58**, 763 (1985).
- Chou, S.Y., H.I. Smith, and D.A. Antoniadis, "X-Ray Lithography for Sub-100-nm-Channel-Length Transistors Using Masks Fabricated with Conventional Photolithography, Anisotropic Etching and Oblique Shadowing," *J. Vac. Sci. Technol. B* **3** (6), 1587, (1985).
- Licini, J.C., D.J. Bishop, M.A. Kastner, and J. Melngailis, "Aperiodic Magnetoresistance Oscillations in Narrow Inversion Layers in Si," *Phys. Rev. Lett.* **55** (27), 2987, Dec. 1985.
- Smith, H.I., "A Statistical Analysis of UV, X-Ray and Charged-Particle Lithographies," *J. Vac. Sci. Technol. B* **4**, 148, (1986).
- Warren, A.C., I. Plotnik, E.H. Anderson, M.L. Schattenburg, D.A. Antoniadis, and H.I. Smith, "Fabrication of Sub-100 nm Linewidth Periodic Structures for Study of Quantum Effects from Interference and Confinement in Si Inversion Layers," *J. Vac. Sci. Technol. B* **4**, 365, (1986).
- Chou, S.Y., H.I. Smith, and D.A. Antoniadis, "Sub-100-nm Channel-Length Transistors Fabricated Using X-Ray Lithography," *J. Vac. Sci. Technol. B* **4**, 253 (1986).
- Chou, S.Y., D.A. Antoniadis, and H.I. Smith, "Observation of Electron Velocity Overshoot in Sub-100-nm-channel MOSFET's in Si," *IEEE Elect. Dev. Lett. EDL-6*, 665, Dec. 1985.
- Kim, H.J., and C.V. Thompson, "Compensation of Grain Growth Enhancement in Doped Silicon Films," *Appl. Phys. Lett.* **48**, 399 (1986).
- Chou, S.Y. and D.A. Antoniadis, "Relationship between Measured and Intrinsic Transconductances of MOSFET's," *IEEE Elect. Dev. Lett.*, submitted for publication.
- Wong, C.C., H.I. Smith, and C.V. Thompson, "Surface-Energy-Driven Secondary Grain Growth in Thin Au Films," *Appl. Phys. Lett.* **48**, 335 (1986).
- Geis, M.W., H.I. Smith, and C.K. Chen, "Characterization and Entrainment of Subboundaries and Defect Trails in Zone-Melting-Recrystallized Si Films," *J. Appl. Phys.*, to be published August 1986.
- Warren, A.C., D.A. Antoniadis, and H.I. Smith, "Quasi-One-Dimensional Conduction in Multiple, Parallel Inversion Lines," *Phys. Rev. Lett.* **56**, 1858 (1986).

Published Conference Proceedings

- Geiss, M.W., C.K. Chen, H.I. Smith, R.W. Mountain, and C.L. Doherty, "Recent Advances in SOI Films Produced by Zone-Melting Recrystallization," Extended Abstracts of the 2nd International Workshop on Future Electron Devices, SOI Technology and 3D Integration (FED SOI/3D Workshop), Shuzenji, Japan, March 19-21, Research and Development Association for Future Electron Devices, 1985, p. 87.
- Stein, J.A., J.A. Rajchman, J. Melngailis, and D.A. Summa, "A Display Based on Switchable Zero Order Diffraction Grating Light Valves," Proceedings of SPIE Conference on Advances in Display Technology V, Vol. 526, p. 105, 1985.
- Wong, C.C., H.I. Smith, and C.V. Thompson, "Secondary Grain Growth and Graphoepitaxy in Thin

- Au Films on Submicrometer-Period Gratings," Proceedings of the Material Research Society, Vol. 47, p. 35, 1985.
- Chou, S.Y., D.A. Antoniadis, and H.I. Smith, "The Use of Shubnikov-de Haas Effect to Investigate Sub-100-nm Channel Lengths in Si MOSFET's," IEEE International Electron Devices Meeting, Washington, D.C., December 1985, pp.562-564.
- Antoniadis, D.A., A.C. Warren, and H.I. Smith, "Quantum Mechanical Effects in Very Short and Very Narrow Channel MOSFET's," IEEE International Electron Devices Meeting, Washington, D.C., December 1985, pp. 558-561.
- Atwater, H.A., H.I. Smith, and C.V. Thompson, "Enhancement of Grain Growth in Ultra Thin Germanium Films by Ion Bombardment," Proceedings of the Fall Meeting Materials Research Society, Boston, Massachusetts, December 2-6, 1985.
- Thompson, C.V. and H.I. Smith, "Secondary Grain Growth in Thin Films," Proceedings of the Fall Meeting Materials Research Society, Boston, Massachusetts, December 2-6, 1985.
- Kim, H.J., and C.V. Thompson, "The Effects of Dopants on Surface-Energy-Driven Grain Growth in Ultrathin Si Films," Proceedings of the Fall Meeting Materials Research Society, Boston, Massachusetts, December 2-6, 1985.
- H.I. Smith, "Crystalline Films on Amorphous Substrates by Zone Melting and Surface-Energy-Driven Grain Growth in Conjunction with Patterning," Proceedings of the Fall Meeting Materials Research Society, Symposium C, Semiconductor-on-Insulator and Thin Film Transistor Technology, Boston, Massachusetts, December 2-6, 1986.

Theses

- Plotnik, I., "Reactive-Ion Etching of Tungsten for sub-50 Nanometer High-Contrast X-Ray Mask Fabrication," S.M. Thesis, Department of Electrical Engineering and Computer Science, M.I.T., June 1985. Also VLSI Memo No. 85-246, M.I.T., May 1985.
- Schott, S.C., "The Behavior of Germanium During Zone-Melting Recrystallization on Various Substrates," S.M. Thesis, Department of Materials Science, M.I.T., June 1985.
- Stein, J.A. "A Micromechanical Optical Switch Based on Zero Order Diffraction for Flat Panel Displays," Ph.D. Thesis, Department of Mechanical Engineering, M.I.T., June 1985.
- Summa, D.A., "An Investigation of Forming of Diffraction Gratings in Thin Polymer Films," S.M. Thesis, Department of Mechanical Engineering, M.I.T., June 1985.
- Warren, A.C., "Surface Superlattices and Quasi-One-Dimensional Conduction in Silicon Inversion Layers," Ph.D. Thesis, Department of Physics, M.I.T., June 1985.
- Us, N.C., "Ion Bombardment in Plasma Processing of Electronic Materials," S.M. Thesis, Department of Materials Science, M.I.T., June 1985. (VI-A, IBM, San Jose, California).