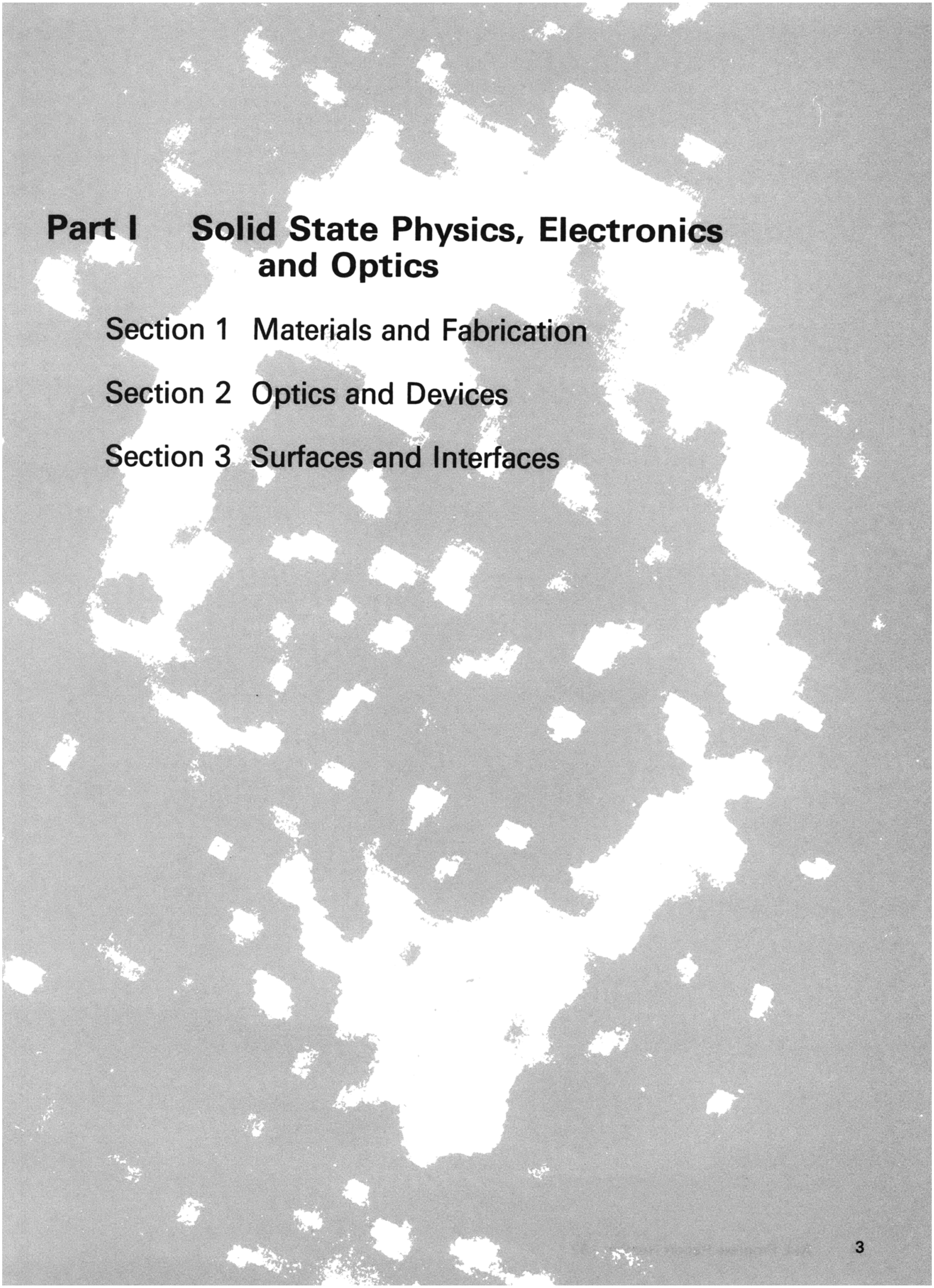

Part I Solid State Physics, Electronics and Optics

Section 1 Materials and Fabrication

Section 2 Optics and Devices

Section 3 Surfaces and Interfaces

Section 1 Materials and Fabrication

Chapter 1. Submicron Structures Technology and Research

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1.1 Submicron Structures Laboratory

The Submicron Structures Laboratory at MIT develops techniques for fabricating surface structures with linewidths in the range from nanometers to micrometers, and uses these structures in a variety of research projects. These projects of the laboratory, which are described briefly below, fall into four major categories: development of submicron and nanometer fabrication technology; nanometer and quantum-effect electronics; crystalline films on non-lattice-matching substrates; and periodic structures for x-ray optics, spectroscopy and atomic interferometry.

1.2 Microfabrication at Linewidths of 100 nm and below

Sponsors

Joint Services Electronics Program
  Contract DAAL03-89-C-0001
National Science Foundation
  Grant ECS 87-09806

Project Staff

Martin Burkhardt, James M. Carter, William Chu, Kathleen Early, Reza A. Ghanbari, Yao-Ching Ku, Alberto Moel, Hui Meng Quek, Dr. Mark L. Schattenburg, Professor Henry I. Smith, Siang-Chun The, Anthony Yen

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A variety of techniques for fabricating structures with characteristic dimensions of 0.1 μm (100 nm) and below are investigated. These include: x-ray nanolithography, holographic lithography, achromatic holographic lithography, electron-beam lithography, focused-ion-beam lithography, reactive-ion etching, electroplating, and liftoff. Development of such techniques is essential if we are to explore the rich field of research applications in the deep-submicron and nanometer domains.

X-ray nanolithography is of special interest because it can provide high throughput and broad process latitude at linewidths of 100 nm and below, something that cannot be achieved with scanning-electron-beam or focused-ion-beam lithography alone. We are developing a new generation of x-ray masks made from inorganic membranes (Si, Si_3N_4, and SiC) in order to eliminate pattern distortion. To achieve multiple-mask alignment compatible with 50 nm linewidths, we will fix the mask-sample gap at 4 μm, translate the mask piezoelectrically, and detect alignment to < 10 nm by a dual-grating interferometric scheme. Phase-shifting x-ray masks should permit us to achieve 50 nm linewidths at such gaps. In previous studies we showed that a pi-phase-shifting mask improves process latitude by increasing the irradiance slope at feature edges. For linewidths below 50 nm we bring the mask membrane into soft contact with the substrate by electrostatic means. A variety of techniques are used to pattern the x-ray masks including e-beam lithography, focused-ion-beam lithography (FIBL), holographic lithography and sidewall shadowing.

Since the early research on x-ray lithography, it was believed that photoelectrons, released when x-ray photons are absorbed, severely limit the resolution of x-ray lithography for linewidths below 100 nm. For example, it was estimated that using the Al_K x-ray (λ = 0.834 nm, E = 1.5 keV), it would not be possible to reliably achieve linewidths below 100 nm. We explored this issue experimentally and found previous estimates to be in error. Figure 1 shows that a 30 nm wide line on an x-ray mask is faithfully replicated with no measurable linewidth change using any one of three x-ray wavelengths, Al_K (0.834 nm), Cu_L (1.33 nm), or C_K (45 nm). The implication is that for linewidths down to ~ 10nm, diffraction and not photoelectron range is the factor that will limit resolution.

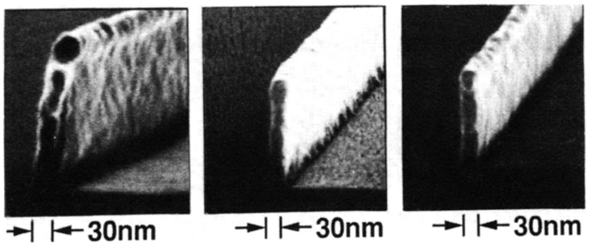

Figure 1. Replication in PMMA of a 30 nm-wide gold absorber line with (a) C_K ($\lambda = 4.5$ nm), (b) Cu_L($\lambda = 1.3$ nm), and (c) Al_K($\lambda = 0.83$ nm).

A new type of achromatic holographic lithography (AHL) was developed that enables us to achieve 100 nm-period gratings (50 nm nominal linewidth). Previously, 200 nm was the minimum period achievable. The AHL scheme is illustrated in figure 2, and the exposure results shown in figure 3. This technology will be used to make gratings for x-ray spectroscopy and atom beam interferometry, and to fabricate new classes of quantum-effect electronic devices.

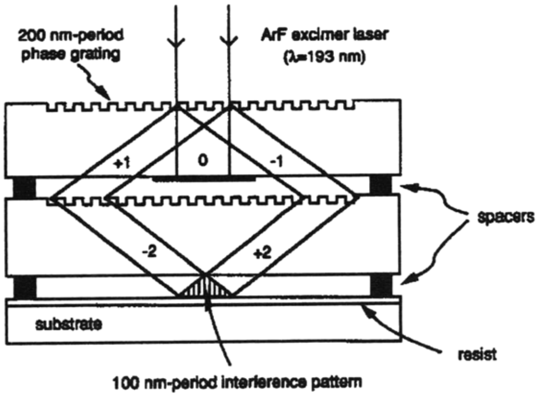

Figure 2. Schematic of the achromatic holographic configuration.

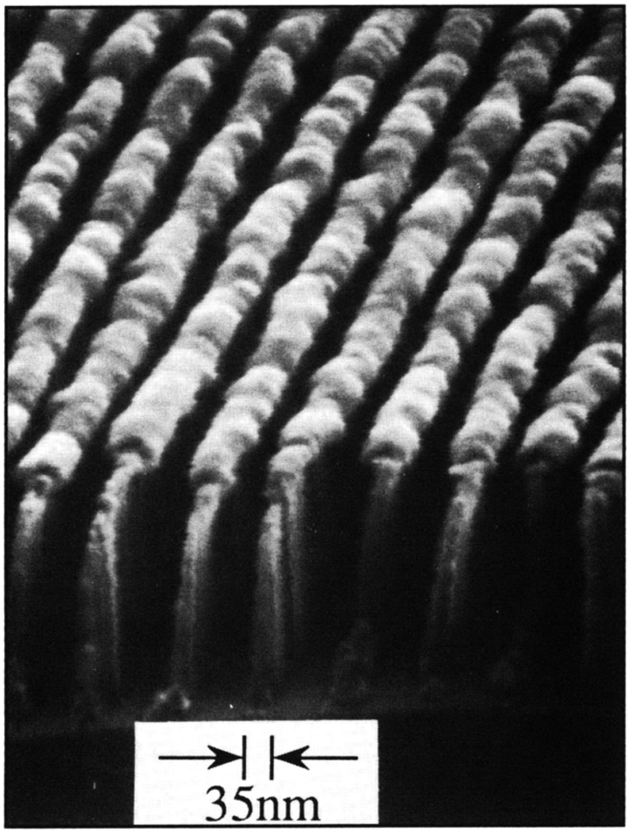

Figure 3. Scanning electron micrograph of 100 nm-period grating lines after exposure, shadow evaporation of nickel and reactive ion etching in an oxygen plasma.

1.3 Improved Mask Technology for X-Ray Lithography

Sponsors

Semiconductor Research Corporation
Contract 87-SP-080
Hampshire Instruments Corporation

Project Staff

Yao-Ching Ku, Kenneth Lu, Professor Henry I. Smith, Lisa Su, JoAnne Gutierrez, Flora S. Tsai

In order to utilize x-ray lithography in the fabrication of submicron integrated electronics, distortion in the x-ray mask must be eliminated. Distortion can arise from stress in the absorber, which is usually gold or tungsten. Tungsten is preferred because it is a closer match in thermal expansion to Si, SiC and other materials used as mask membranes. However, W is usually under high stress when deposited by evaporation or sputtering. Earlier, we demonstrated that for a given type of substrate, zero stress (i.e., less than 5×10^7 dynes/cm^2) can be achieved by controlling the sputtering pressure to within one-tenth of a militorr. We are now developing a computer-controlled system for monitoring in situ, during deposition, the stress in sputtered W on x-ray mask membranes. Stress is determined from the resonant frequency of the membrane.

We have also investigated a number of materials as mask membranes including: Si, Si_3N_4, SiC, and laminates of Si_3N_4/poly Si/Si_3N_4 and $SiO_2/Si_3N_4/SiO_2$. The strongest membranes were Si rich Si_3N_4. A 1.2 μm thick membrane of this material can sustain a full atmosphere pressure differential across a span of 20 mm. There is a concern, however, that Si_3N_4 will undergo stress changes during the heavy x-ray irradiation anticipated in IC production. We are investigating this issue as well as novel approaches to enhance the durability of Si membranes.

1.4 Study of Electron Transport in Si MOSFETs with Deep-Submicron Channel Lengths

Sponsor.

Joint Services Electronics Program
Contract DAAL03-89-C-0001

Project Staff

Professor Dimitri A. Antoniadis, Gregory A. Carlin, Paul G. Meyer, Ghavam Shahidi, Professor Henry I. Smith, Siang-Chun The

Electronic conduction in sub-100 nm channel length Si MOSFETS is being studied in order to observe non-stationary transport effects, i.e., effects arising from rapid spatial variation of the electric field, and the resulting disparity between the actual carrier temperature and the temperature that would correspond with the given field at steady-state conditions. In simple terms, non-stationary effects are observed when transit times across the very short channels become comparable to, or shorter than, energy relaxation times. Previous work has produced NMOS devices with channel lengths down to 60 nm and gate oxides as thin as 2.5 nm. The devices were fabricated with a combination of x-ray nanolithography and optical projection lithography. Electron velocity overshoot and a reduction of hot-electron effects, as measured from the substrate current, were observed in these devices.

Our focus has now shifted to the fabrication of self-aligned deep-submicron MOSFETs. These devices will use polysilicon gates and cobalt salicidation (self-aligned silicidation). The aim is to reduce parasitic source and drain resistances and gate-source overlaps. This will permit a clearer observation of the non-stationary effects, e.g., in both substrate and gate currents, and will enable us to push device switching speed.

Deep-submicron self-aligned silicided NMOS devices have been successfully fabricated using optical projection lithography followed by partial photoresist ashing to define small features. Devices with effective channel lengths down to 230 nm were fabricated using this technique. As in the non-self-aligned device process, both boron and indium were used as implant species to control punchthrough and threshold voltage. The sheet resistance of the source-drain regions was reduced by silicidation from 110 to 13.6 Ohms per square, and source-drain contact resistances on the devices were reduced from 52 to 10.7 Ohms.

The self-aligned NMOS process is undergoing further development to include x-ray nanolithography for gate polysilicon patterning. This has included the development of inorganic x-ray mask technology to avoid distortion and achieve precise alignment. A simple optical scheme to align x-ray masks to substrates to less than 1 μm has also been developed. The absorber on the x-ray mask will be patterned using a combination of optical lithography and focused-ion-beam (FIB) lithography. In addition, an effort is being made to further improve consistency and control in the salicidation process.

Work is also in progress to develop a corresponding deep-submicron self-aligned PMOS process. This should give us 100 nm-channel-length CMOS circuits fabricated by a technology compatible with commercial mass production.

1.5 Studies of Electronic Conduction in One-Dimensional Semiconductor Devices

Sponsors

Joint Services Electronics Program
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National Science Foundation
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Project Staff

Professor Dimitri A. Antonaidis, Stuart B. Field, Professor Marc A. Kastner, Udi Meirav, Samuel L. Park, John H.F. Scott-Thomas, Professor Henry I. Smith

Sophisticated processing techniques and advanced lithography have allowed us to enter what we believe is a fundamentally new regime in the study of electronic conduction in one-dimensional systems. A slotted-gate MOSFET structure (figure 4) was used to produce an electron gas at the Si/SiO_2 interface beneath the gap in the lower-gate. This was done by biasing the upper gate positively, while keeping the slotted gate just below threshold. Fringing fields around the lower gate confined the electron gas to a width substantially narrower ($\sim$ 25 nm) than the distance separating the two halves of the slotted gate ($\sim$ 70 nm). The slotted gate was produced using x-ray nanolithography and liftoff. It was composed of refractory metals to allow a subsequent high temperature anneal. This anneal removed damage created by the e-beam evaporation of the refractory metal, so that the electron gas had a mobility of 15,000 cm^2 / V-sec at 4.2K. The electrical conductance of the 1-D gas was measured as a function of the upper gate voltage for temperatures less than 1K, and a surprising series of periodic oscillations was seen in the conductance (figure 5). Changing the gate voltage can be thought of as changing the number of electrons per unit length of electron gas. Since the conductance is thermally activated, the oscillations reflect a periodic change in the activation energy of the electron gas as the electron density is changed. Computer simulations solving Poission's equation and the single particle Schrodinger

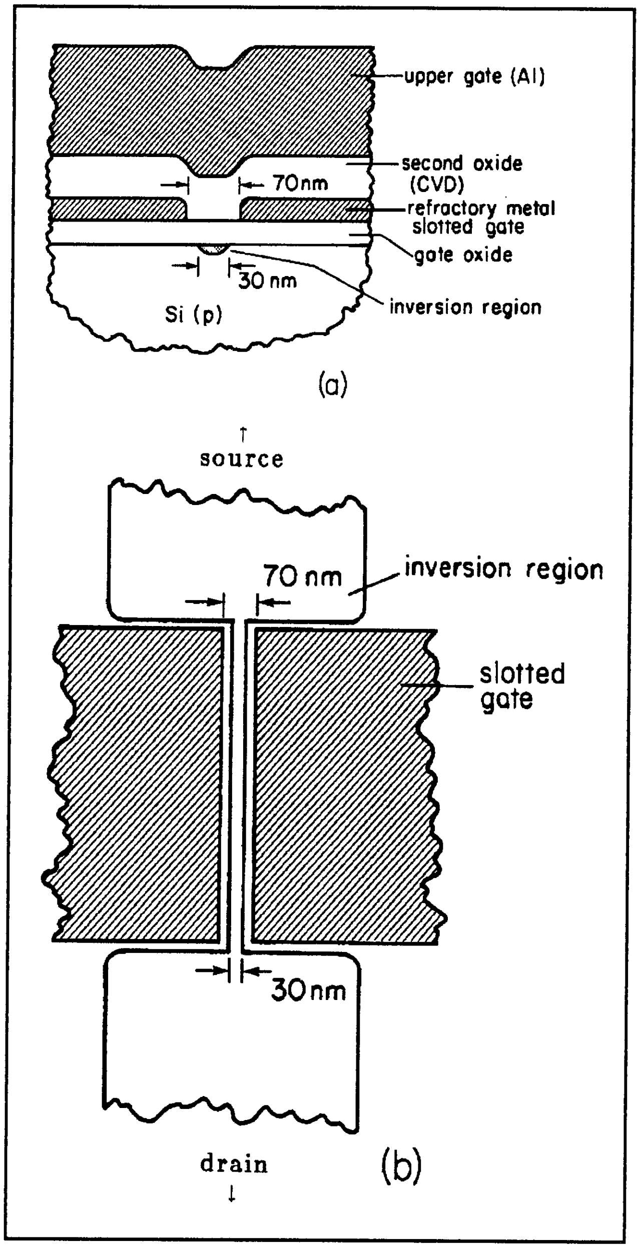

Figure 4. (a) Schematic cross section and (b) top view of the slotted-gate device. The inversion layer, formed by the positively biased upper gate is confined by the lower gate. The thermal oxide and refractory metal lower gate are both 30 nm thick, and the chemical vapor deposition oxide is 45 nm thick. The width of a narrow inversion layer is exaggerated in (b).

wave equation strongly suggest that the electron gas is dynamically one-dimensional when the oscillations are most strongly seen. That is, the electrons are in the lowest quantum energy level of the potential well created by the fringing fields of the slotted gate.

A one-dimensional electron gas will form a charge density wave (CDW) when the electron-electron interaction is the dominant energy. This is the same regime that the device is in when the oscillations are seen. In a CDW, electrons are spaced periodically. This minimizes the total energy of the electron gas. Impurities in the device can pin the CDW. Two impurities in the conducting channel would in turn strongly pin and weakly pin the CDW as the electron density of the gas is changed. This corresponds to commensurability and incommensurability of the CDW with the spacing of the impurities, and results in oscillatory behavior of the conductance with electron density. The period of the oscillations varies randomly from device to device, with no dependence on length. The period changes in the same device when it is heated to room temperature and then cooled. This strongly suggests that mobile impurity atoms are doing the pinning. It should be stressed that these oscillations are seen with no magnetic field, implying

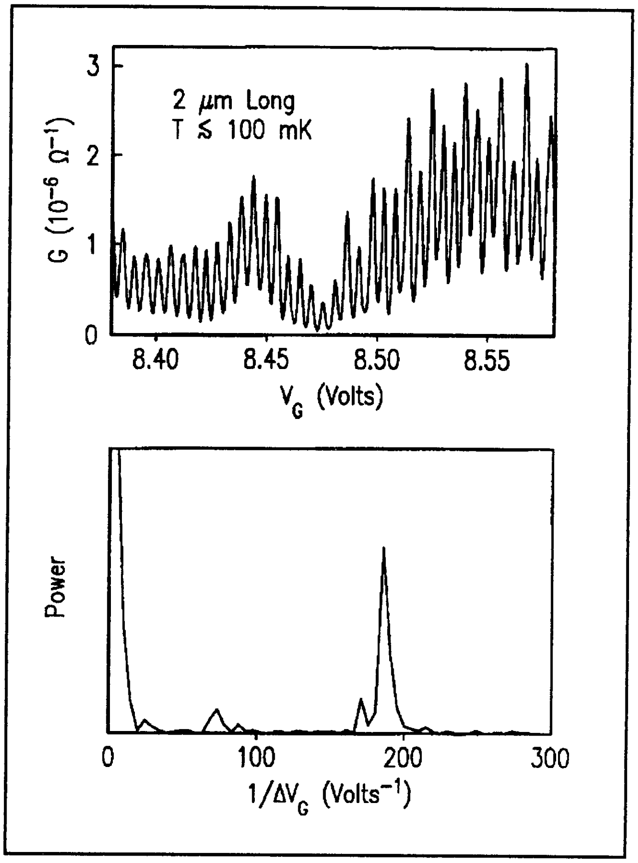

Figure 5. Top panel: Conductance G versus gate voltage V_G for a 2 μm-long inversion layer. Bottom panel: Fourier power spectrum of the top panel data.

that the phenomenon is fundamentally different from phenomena requiring Landau quantization (such as the Quantum Hall Effect). Also, the effect seems to require a many-body theory (i.e., one incorporating electron-electron interactions).

1.6 Surface Superlattice Formation in Silicon Inversion Layers Using 0.2 μm-Period Grating-Gate Field-Effect Transistors

Sponsors

Joint Services Electronics Program
Contract DAAL03-89-C-0001
U.S. Air Force - Office of Scientific Research
Grant AFOSR-88-0304

Project Staff

Professor Dimitri A. Antoniadis, Phillip F. Bagwell, Professor Marc A. Kastner, Professor Terry P. Orlando, Professor Henry I. Smith, Anthony Yen

We have been studying distinctly quantum mechanical effects in electrical conduction using the silicon grating-gate field-effect transistor (GGFET). The Si GGFET is a dual stacked-gate MOS-type structure in which the gate closest to the inversion layer (bottom gate) is a 200 nm period grating made of refractory metal. A SiO_2 insulating layer separates the grating gate and the inversion layer from a second continuous aluminum gate (top gate). Two types of electronic devices are possible in this geometry: (1) a lateral surface superlattice (LSSL) GGFET in which carrier conduction is perpendicular to the grating lines; and (2) a quasi-one-dimensional (QID) GGFET which confines carriers to move in narrow inversion strips beneath the grating lines.

Here we describe our observation of a transition from conduction through ~ 300 multiple parallel quantum wires to conduction in a 2D electron gas (standard MOSFET) using the Q1D GGFET. We can induce such a dimensional transition by varying the two gate voltages of the GGFET. When a strong magnetic field is applied perpendicular to the plane of the inversion layer at temperatures below 4.2K, we observe a large negative transconductance whose onset voltage marks the transition from 1D to 2D conduction.

This is shown in figure 6, where the transition from 1D to 2D behavior occurs at a top-gate voltage around zero volts. The significant observation is that with a magnetic field perpendicular to the plane of the channel, adding more electrons to the MOSFET actually reduces the device conductance at the 1D to 2D transition point. The oscillations below the transition point are due to magnetoelectric subbands, while those above the transition are due to Shubnikov de Haas oscillations as the Landau levels pass through the Fermi level. This striking dimensional transition in a magnetic field has never been observed before.

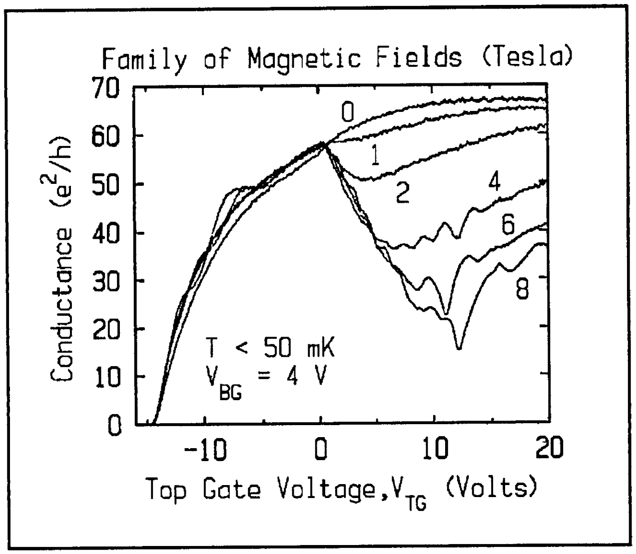

Figure 6. Plot of the conductance of a quasi-1D grating-gate MOSFET as a function the top gate voltage, for several values of the perpendicular magnetic field. At a top gate voltage around zero volts there is a transition from 1D to 2D conduction with an attendant strong negative transconductance.

The origin of the unusual magnetoresistance effects that we have observed is still unclear. At the magnetic fields where the effect becomes prominent, the cyclotron radius is much smaller than the width of the quantum wires, so a semiclassical explanation involving an interplay of the cyclotron radius and wire width is probably inappropriate. Also, the two terminal magnetoresistance measurements significantly complicate interpretation of the data. A noninvasive four-terminal measurement would be ideal, but it is not clear that such a measurement is possible. Finally, the exact way in which the current feeds into the source contact from the bulk device may also be important. At higher magnetic fields where the magnetoconductance oscillations begin to appear, conduction takes place through edge states. These edge states may also play a role in giving rise to the effect.

1.7 Study of Surface Superlattice Formation in GaAs/GaAlAs Modulation Doped Field-Effect Transistors

Sponsor

U.S. Air Force - Office of Scientific Research
Grant AFOSR-88-0304

Project Staff

Professor Dimitri A. Antoniadis, Martin Burkhardt, William Chu, Professor Jesus A. del Alamo, Reza A. Ghanbari, Khalid Ismail, Professor Marc A. Kastner, Professor Terry P. Orlando, Professor Henry I. Smith, Anthony Yen

We have used the modulation-doped field-effect transistor (MODFET) as a test vehicle for studying quantum effects such as electron back diffraction in a GaAs/AlGaAs material system. In a conventional MODFET the current transport is modulated by a continuous gate between source and drain. In our studies, we have used Schottky metal gratings and grids for the gate, as illustrated in figure 7. Such gates produce a periodic potential modulation in the channel.

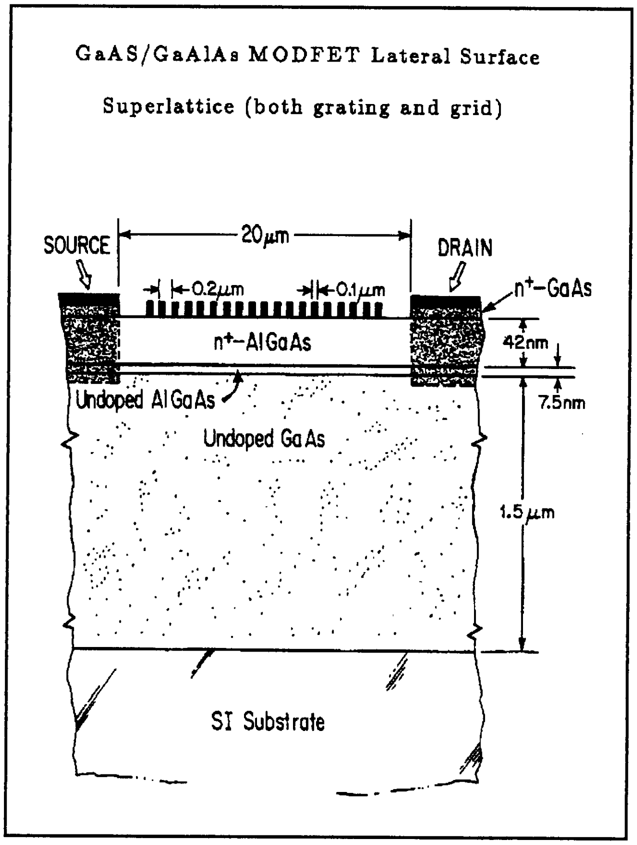
GaAS/GaAlAs MODFET Lateral Surface Superlattice (both grating and grid)

Figure 7. Schematic cross section of a grid-gate MODFET device. Contacts to the grid are made by pads off to the sides of the conduction channel.

The grid was produced by x-ray nanolithography and liftoff. The x-ray mask of the grid was produced by two successive x-ray exposures, at 90 degrees to one another, using a master mask that was fabricated via holographic lithography. The latter yields coherent gratings over areas several centimeters in diameter. A new technique was developed that yields grating and grid patterns only in the channel region between source and drain. This has simplified the overall process and enhanced its reliability.

The MODFET is normally on, that is, a negative gate bias of about -0.2 V must be applied to pinch off conductance from source to drain. As the gate bias is raised above this threshold point, the height of the periodic potential modulation is reduced and, simultaneously, the Fermi energy is raised (or, equivalently, the electron wavelength is reduced) in the 2D electron gas residing at the AlGaAs/GaAs interface. When the electron wavelength phase-matches the periodic potential, electron back-diffraction occurs provided the inelastic length (i.e., the coherence or phase breaking length) is longer than the grating-period. Such back diffraction is manifested by a drop in the conductance. A stronger back diffraction effect is observed in the case of a grid because true minigaps are formed. The measurements of conductance modulation of grating and grid-gate MODFETs agrees with theoretical predictions. In the grid gate devices it was also possible to observe negative differential resistance which might be due to sequential resonant tunneling.

We plan to decrease the periodicity of the gratings and grids by a factor of two, to 100 nm period. For devices with such fine grating periodicity the superlattice effect should become more pronounced and observable at higher temperatures. We will also conduct magnetotransport measurements with devices of 100 and 200 nm periodicity.

1.8 Study of One-Dimensional Subbands and Mobility Modulation in GaAs/AlGaAs Quantum Wires

Sponsors

Joint Services Electronics Program
Contract DAAL03-89-C-0001
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Project Staff

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In order to study one-dimensional conductivity in the AlGaAs/GaAs modulation-doped structure without the conductance fluctuations normally associated with single microscopic systems, we fabricated arrays of 100 parallel quantum wires (MPQW). The measured Hall mobility in the 2-D electron gas at the AlGaAs/GaAs interface was 250,000 cm^2/Vs at 4.2K. The multiple quantum wires were produced by x-ray nanolithography, liftoff of Ti/Au, and ion etching of the AlGaAs. The charge concentration in the quantum wires could be increased by applying a positive bias to a back-side contact or by illumination. (There was no persistent photocurrent in these samples).

Figure 8 shows the measured drain-source current versus backgate bias for the quantum wires (solid line) and for an equivalent 2-D device (dashed line). To explain the structure, we have developed a semi-classical model to calculate the conductivity of these devices. As seen in the dotted line in figure 8, our calculations match the measured data quite well.

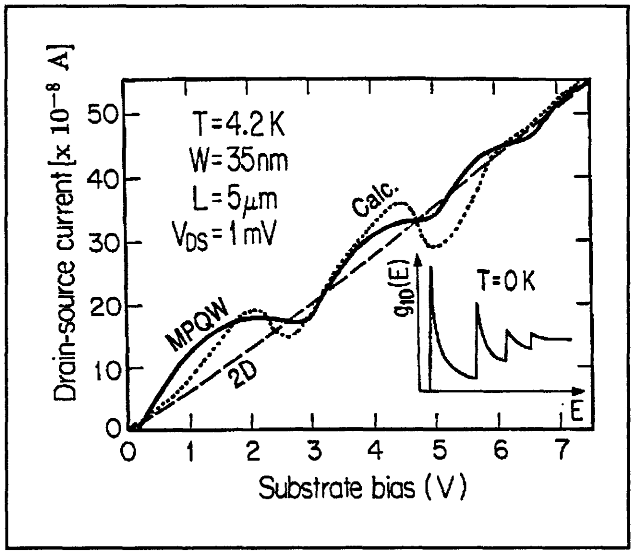

Figure 8. Drain-source current (I$_{DS}$) as a function of substrate bais (V$_{SUB}$) for the multiple parallel quantum wires (solid line) and scaled down 2D channel (dashed line). The inset shows the theoretical density of states in a Q1D wire at 0 K. The dotted line is an analytical calculation.

Based on our calculations, we conclude that the observed mobility modulation is associated with populating the quasi-one-dimensional subbands. The negative differential transconductance regions arise when higher subbands begin to be populated. Currently, we are working on fabricating new versions of these devices that allow for control of the confining potential, and hence the position of the subbands, by use of a top gate. It is hoped that these devices will verify the validity of our model.

1.9 Arrays of Field-Effect-Induced Quantum Dots

Sponsors

Joint Services Electronics Program
Contract DAAL03-89-C-0001
U.S. Air Force - Office of Scientific Research
Grant AFOSR-88-0304

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A metal grid on a modulation-doped AlGaAs/GaAs substrate (depicted in figure

9a) produces a two-dimensional periodic potential modulation at the AlGaAs/GaAs interface via the Schottky effect. If a gate electrode is attached to the grid, the potential can be further modified with an external voltage source. By changing the gate voltage from positive to negative values, the potential seen by the electrons located at the AlGaAs/GaAs interface can be varied from uniform (in which case the electrons behave as a 2-D electron gas) to weakly coupled zero-D quantum wells (figure 9b) to isolated zero-D quantum dots (figure 9c). We have made such structures, with spatial periods of 200 nm in both orthogonal directions using technology similar to that described in Section 1.7, but now the grid gate occupies an area of several square millimeters. The isolated quantum dots and the attendant zero-dimensional electronic subbands were examined in collaboration with D. Tsui at Princeton University using far-infrared (FIR) cyclotron resonance. Transitions between the discrete energy levels in the quantum dots were observed as a function of magnetic field. Results were in agreement with a theoretical model.

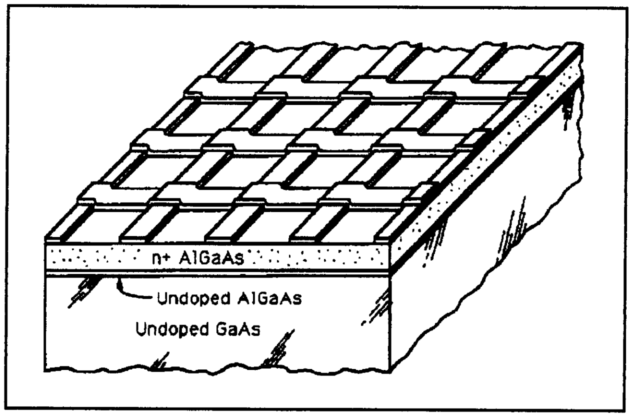

Figure 9a. Metal grid gate on a modulation-doped AlGaAs/GaAs substrate.

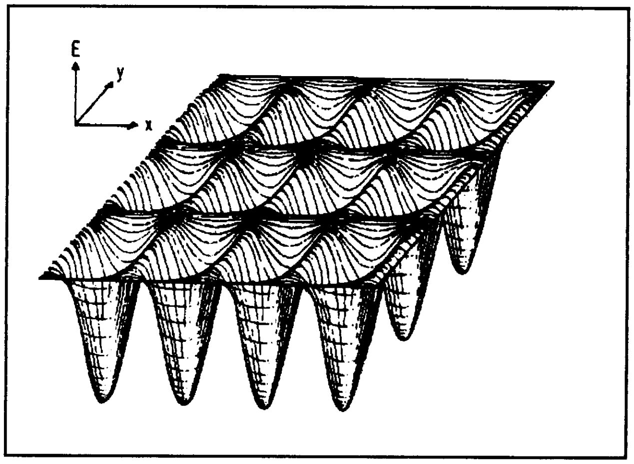

Figure 9b. Depiction of potential seen by electrons at the AlGaAs/GaAs interface for weakly coupled quantum dots.

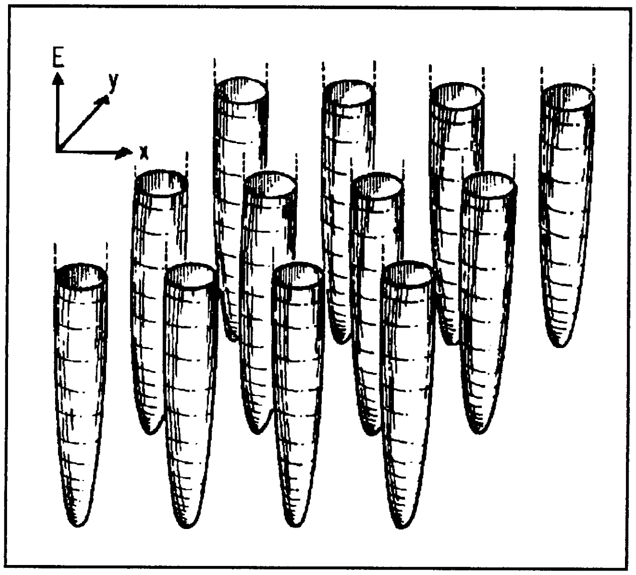

Figure 9c. Potential for the case of isolated quantum dots.

In collaboration with T.P. Smith and K. Ismail at IBM we applied a magnetic field perpendicular to the plane of the grid gate and measured magnetocapacitance as the gate voltage was swept, changing the electronic system from two-dimensional to coupled quantum wells, to insolated quantum dots. The normal oscillations due to Landau level filling are strongly suppressed when the Fermi level lines up with the minibandgaps. Thus, these measurements give important confirmation of the minband structure we observed earlier in transport. In the weakly-coupled-quantum-dot regime the magnetocapacitance oscillations show evidence of fractal behavior when the number of flux quanta per unit cell of our grid is a rational number (i.e., 1/2, 1/3, 3/5, etc.).

We are currently fabricating a new set of grid-gate MODFETS, using an improved fabrication process and will study their transport, capacitance, and absorption properties as a function of magnetic field.

1.10 Planar-Resonant-Tunneling Field-Effect Transistors (PRESTFETs)

Sponsor

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

Project Staff

Professor Dimitri A. Antoniadis, William Chu, Khalid Ismail, and Professor Henry I. Smith

Encouraged by the observation of negative differential resistance in the surface-superlattice MODFET (Section 1.7), we have proceeded to fabricate and test a double-barrier MODFET shown schematically in figure 10. Under the gate electrodes, the energy level diagram is as sketched in figure 11. With proper biasing, resonant tunneling should be observable, hence the name of the device PRESTFET (Planar-Resonant Tunneling Field-Effect Transistor).

Three types of measurements were performed (at 4.2 K) on a PRESTFET device in which the gate electrodes were 60 nm long and separated by 60 nm: (1) gate electrodes are connected together, the drain-to-source voltage is held fixed (< 5 mV), and the gate voltage is swept; (2) the electrodes are connected together and the intensity of an illuminating LED is scanned; (3) one gate bias is fixed while the other is swept.

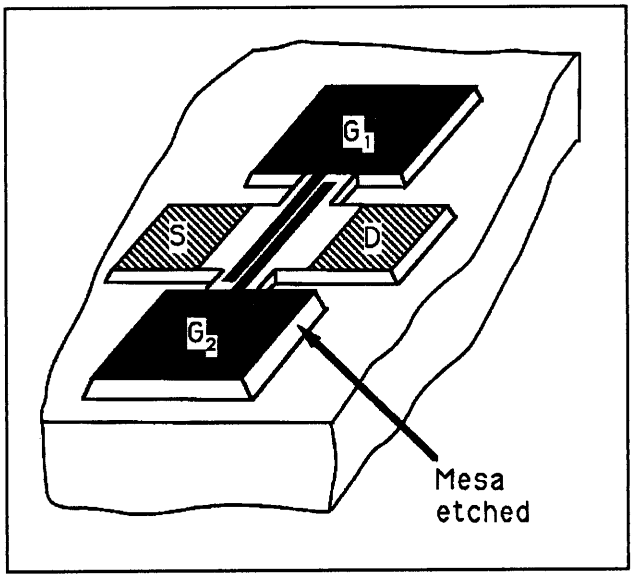

Figure 10. Sketch of the layout of a 4-terminal, double-barrier, planar-resonant-tunneling field-effect transistor (PRESTFET).

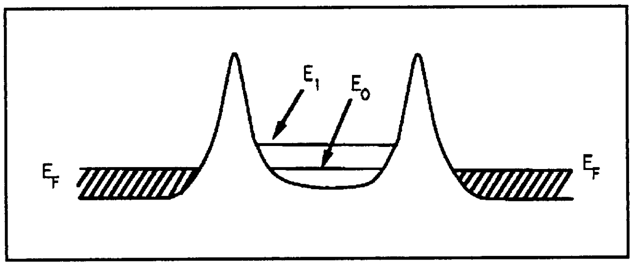

Figure 11. Energy level diagram of a symmetric, double-barrier PRESTFET.

In all three cases, clear resonances were observed in the drain-to-source current. In figure 12, a plot of the results of the third experiment is shown. The results of these three measurements provide clear evidence that resonant tunneling occurs through the quantized well states.

We are currently fabricating PRESTFET devices with even finer electrodes and developing a high-throughput PRESTFET fabrication process using x-ray nanolithography.

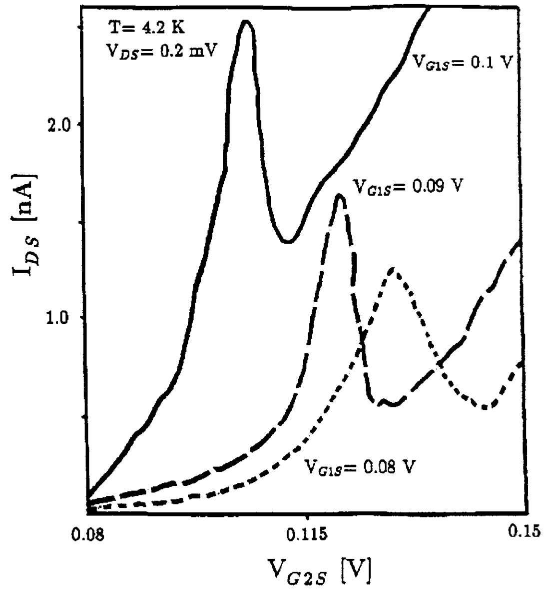

Figure 12. Drain-source current as a function of bias on gate 2 for three different bias conditions, below threshold, on gate 1.

1.11 Submicrometer-Period Gold Transmission Gratings for X-Ray Spectroscopy and Atom-Beam Interferometry

Sponsor

Joint Services Electronics Program
Contract DAAL03-89-C-0001
X-Opt., Incorporated

Project Staff

Dr. Mark L. Schattenburg, Professor Henry I. Smith

Gold transmission gratings with periods of 0.2 to 1.0 μm, and thicknesses ranging from 0.1 to 1 μm are fabricated using x-ray lithography and electroplating. The x-ray masks are made with holographic lithography. Transmission gratings are either supported on thin (1 μm) membranes or are made self-supporting by the addition of crossing struts. They are supplied to external laboratories for spectroscopy of the x-ray emission from a variety of sources. Over 15 laboratories around the world are using MIT-supplied gratings, and this project constitutes the sole source for these diffractors. Self-supporting transmission gratings in both gold and thin-film chromium are being provided to Professor David Pritchard's group for use in experiments to study the diffraction of neutral sodium atoms by gratings. The sodium atoms have a de Broglie wavelength of ~ 17 pm. Clear demonstrations of atomic diffraction have been made with these gratings. The gratings can also be used to divide and recombine an atomic beam coherently, and may provide the easiest route to the realization of an atom wave interferometer.

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

Sponsor

National Aeronautics and Space Administration
Contract NAS8-36748

Project Staff

Professor Claude R. Canizares, Dr. Mark L. Schattenburg, Professor Henry I. Smith

Gold gratings with spatial periods of 0.1 to 1.0 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) that will be launched in the mid-1990s. 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 to 1. To achieve this, we first expose a grating pattern in 1.0 μm-thick PMMA over a gold plating base using x-ray nanolithography. Gold is then electroplated into the spaces of the PMMA to a thickness up to 1 μm. Flight prototype gratings have been fabricated and undergone space-worthiness tests. In the initial stage of this program we used the carbon K x-ray ($\lambda = 4.5$ nm) which required that the mask and substrate be in contact to avoid diffraction. This, in turn, caused distortion of the grating. To avoid this problem we are developing a new technology of microgap x-ray nanolithography using the copper L x-ray (λ = 1.33 nm) and Si_3N_4 membrane masks.

1.13 Epitaxy via Surface-Energy-Driven Grain Growth

Sponsor

AT&T Bell Laboratories
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Project Staff

Jerold A. Floro, Professor Henry I. Smith, Professor Carl V. Thompson

Epitaxial grain growth (EGG) in polycrystalline thin films on single crystal substrates is being investigated as an alternative process for obtaining and studying epitaxy. EGG can produce smoother epitaxial films than in conventional epitaxy and in some cases may yield lower defect densities as well. In addition, EGG can produce unique non-lattice-matched orientations not observed in conventional epitaxy. Thin film epitaxy is conventionally obtained by vapor deposition at low rate onto a single-crystal substrate held at elevated temperature, resulting in a single-crystal film as-deposited. In contrast, we deliberately deposit films at high rates and low temperatures in an ultra-high vacuum electron-beam evaporator in order to obtain polycrystalline films. These films can then be annealed in situ to promote epitaxial grain growth.

EGG occurs because the anisotropic film/single-crystal substrate interfacial energy selects one film crystallographic orientation as having the lowest total free energy. Grains in this orientation thus have the largest driving force for growth and will predominate as the system coarsens.

We are currently studying EGG in model systems known to exhibit conventional epitaxy, e.g., Au, Al, Cu, and Ag films on mica and alkali halide substrates. The following results have been obtained: (1) EGG occurs in all these systems, (2) in the case of Au on mica EGG results in a smoother, lower defect density film than a corresponding conventional epitaxial film, (3) the final orientation selected by EGG is determined by the energy of the film's free surface as well as the film/substrate interface, (4) the final orientation selected by EGG is not necessarily the same orientation observed in conventional epitaxy, implying that conventional epitaxial orientations can be metastable. In the case of Au on (100) NaCl, (111) epitaxial Au grains grow, whereas conventional epitaxy yields a (100) film.

We have developed a coarsening theory which is applicable to epitaxial grain growth. This theory derives a growth law for interface-controlled coarsening of coplanar disks, including terms accounting for surface energy anisotropy. This growth law may then be used to computationally solve the continuity equation for grains in size space in order to monitor the time evolution of the grain size and orientation distribution. Use of an appropriate interface energy function will allow comparison with experiment.

1.14 Publications

1.14.1 JSEP Publications

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