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STUDY OF QUANTUM MECHANICAL EFFECTS IN DEEP SUBMICRON,
GRATING-GATE FIELD EFFECT TRANSISTORS

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STUDY OF QUANTUM MECHANICAL EFFECTS IN DEEP SUBMICRON,
GRATING-GATE FIELD EFFECT TRANSISTORS

Grant No. AFOSR-85-0376A

Final Technical Report
September 30, 1985 through September 29, 1988

Personnel: Prof. Dimitri A. Antoniadis (Co-PI)
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This research program investigates the effect of extreme submicron spatial modulation of the electrostatic potential on the transport of 2-D electrons in silicon and in III-V heterojunction semiconductor devices. The test vehicle is the so-called periodic gate FET (PGFET), with gates consisting of either a grating or a grid, with 200 nm periodicity. When electrons are made to move in a direction perpendicular to the potential modulation, i.e., perpendicular to the grating or along the grid axis, they exhibit a surface superlattice (SSL) effect. When moving along the potential modulation electrons are restricted to only one degree of freedom and thus constitute a quasi-one-dimensional (Q1D) system. Grid-gate FET's have been found to exhibit substantially stronger SSL behavior than their grating-gate counterparts. Finally, electron transport in quantized and spatially periodic systems has been studied theoretically and new insights and quantitative calculations have been obtained.

A. Silicon grating-PGFETs

Our efforts have been focused on fabricating and characterizing surface superlattice (SSL) and quasi-one-dimensional (Q1D) periodic gate field effect transistors (PGFETs). The first working devices were completed in June 1987. Device yield was good due to the processing improvements described below. We have also achieved our goal of building very high mobility MOSFETs despite prolonged exposure to x-rays during fabrication. We anneal x-ray damage in vacuum at 950 °C without deterioration of the gate wires due to either oxidization or growth of large grains. Our experiments last year in the metallurgy of various refractory metal combinations was crucial to the development of this technology. The inversion layer electron mobility for our

devices was measured to be about $1000 \text{ cm}^2/\text{V.S}$ at room temperature and $15000 \text{ cm}^2/\text{V.S}$ at 4.2 K. These devices are possibly the highest mobility MOSFETs made using either e-beam or x-ray lithography. High electron mobility is needed to obtain the long elastic and inelastic diffusion lengths necessary to observe features in conductivity due to the wave nature of the electrons.

The silicon PGFET's dual-stacked gate MOS structure is very advantageous for experiments involving both the SSL and Q1D. In the case of the SSL, the dual gate allows independent control of the average electron density in the inversion layer and of the strength of the periodic modulation. In Q1D devices the dual gate allows the formation of inversion strips between gate wires. This permits easy control of the inversion layer width. The feature distinguishing the Q1D PGFET is its relative insensitivity to the sample-specific fluctuations characteristic of other MOSFETs built to study electronic conduction in single narrow inversion layers. The signal-to-"noise" ratio should increase as one over the square root of the number of incoherent regions in the device. The primary feature which distinguishes the SSL PGFET from other superlattices, such as those fabricated using molecular beam epitaxy, is that both the strength of the periodic modulation and the Fermi level can be controlled independently. In sharp contrast to systems attempting to emulate static crystal properties, the SSL PGFET functions as a "voltage controlled crystal."

In direct measurements of transconductance by means of a lock-in amplifier, we have observed reproducible structure on planar as well as PGFET devices, which we believe to be the so-called "universal" conductance fluctuations of Lee and Stone. They are unavoidable in any metallic system with a finite mean free path. In order to observe features in conductance, such as those from one-dimensional subbands or electron back diffraction from a periodic potential, they must be larger than the characteristic size of the natural conductance fluctuation.

Strong modulation of the silicon inversion layer requires strong control of the device current from both gates. Two deficiencies in our devices were: (1) the grating appears to have wide lines and narrow spaces, and (2) the top gate is relatively far away from the inversion layer (200 nm). Thus the top gate did not have as strong a control as in the earlier devices of Warren. This is due to competition of fringing fields in the region between grating wires. New PGFETs in silicon with small wire widths and upper dielectric thickness of 50 nm, are scheduled for completion beyond the end of this three year grant.

B. III-V PGFETS

Three different types of III-V Quantum Effect Devices have been successfully fabricated during the course of this project: grating-gate surface-superlattice (SSL) MODFETs, multiple parallel quasi-one-dimensional (Q1D) conductors, and grid-gate SSL. All material was grown with the help of

the MBE group under Professor Fonstad at MIT.

The grating-gate devices showed plateau-like features in their turn-on characteristics at 4.2 K. The effect was observed in all measured devices. On the same sample, and with minor modifications to the SSL process, we managed to fabricate Q1D conductors by periodically etching into the top AlGaAs layer of the modulation doped structure. The defined lines were 100 nm wide, but the effective width, deduced from the conductance, was only 30 nm. The charge concentration could be changed by means of a substrate contact or by light emitted by an LED. At 4.2 K clear evidence of subbands could be deduced by measuring the current as a function of either substrate bias or light intensity. We also observed at certain currents a mobility in the Q1D devices that use higher than the 2D mobility, an effect predicted by Sakaki. In brief, in Q1D structure the density-of-states decreases as the fermi level is raised, and this reduces the scattering probability.

The first generation of grid-gate devices was fabricated using a double exposure of two perpendicular gratings. Although the yield was not as high as with the grating-gate devices, the superlattice effect at 4.2 K was much stronger, and negative differential transconductance was observed for the first time. A similar nonlinear effect was observed in the current vs. drain bias curve, at a gate bias close to threshold. In addition, there was a negative differential resistance at higher lateral fields, which could be a manifestation of sequential resonant tunneling through part or all of the grid. Interestingly, a plateau feature in the I.V characteristic could be observed at 77 K where the negative differential resistance was at 4.2 K. This may be the first manifestation of resonant tunneling in an artificial lateral structure and may have significant implications in terms of the realization of lateral resonant tunneling transistors.

Recently we have been able to fabricate an X-ray mask with a grid absorber, such that only one exposure was needed. Using this mask we have fabricated more grid-gate devices with higher yield. We also established a cooperation with D. Tsui at Princeton to characterize the grid-gate LSSL using cyclotron resonance experiments. For this purpose, a 4-probe device with a 4mm X 4mm area, covered by a 200-nm-period Schottky grid was fabricated on top of the modulation doped layers. The devices operated successfully in terms of the gate modulation of the charge, and further experiments will be performed to characterize the devices.

C. Theory - Modeling of Surface Superlattice Transport

We have developed a semiclassical model for electron transport in periodic and quasi one dimensional structures that allows us to understand the most important effects of weak disorder, finite temperature, and the addition of free electron motion perpendicular to the superlattice in the grating gate devices. The current-voltage characteristics of grid gate devices are also calculable in this model. The model's main advantages are that it (1) greatly aides conceptual understanding of the devices by expressing most important quantities in terms of mathematical convolutions (2) is valid for the typical incoherent regime of electronic transport in which the inelastic length is much smaller than the sample size but longer than the grating period (3) makes it possible to compute the I-V curves for the surface superlattice and quasi one dimensional transistors when combined with a semiclassical device simulator. The model's main weakness is that it is only valid at low drain source voltages. A very important insight we have gained using this model is that quantum electronic devices are limited primarily by incoherent processes such as inelastic scattering and finite temperature and not by elastic scattering.

Destruction of most electron wave interference effects in the electrical conductivity, including standing waves set up by diffraction from a superlattice, comes from averaging the conductivity over each coherent region of the sample. Thus a sample in which the the electron coherence length is small compared with the sample size is called 'self-averaging', because it carries out the ensemble average over all the different arrangements of defects inside each coherent region. The effect this incoherence is to average the conductivity and density of states over a width in energy \hbar/τ where τ is the *elastic* mean free time. The subtle point here is that inelastic processes give rise to a broadening whose width is determined by the elastic mean free time. The broadening is called elastic, yet depends on the existence of inelastic processes.

We can mathematically express both elastic broadening and thermal broadening as a convolution with the impurity spectral function $A(E, \hbar/\tau)$ and the negative derivative of the Fermi-Dirac distribution function $-\partial f(E, k_B T)/\partial E$.

$$N(\bar{E}, \hbar/\tau, k_B T) = N(\bar{E}) \otimes A(\bar{E}, \hbar/\tau) \otimes \left(-\frac{\partial f}{\partial \bar{E}}(\bar{E}, k_B T) \right) \quad (1)$$

$$\sigma(\bar{E}, \hbar/\tau, k_B T) = \sigma(\bar{E}) \otimes A(\bar{E}, \hbar/\tau) \otimes \left(-\frac{\partial f}{\partial \bar{E}}(\bar{E}, k_B T) \right) \quad (2)$$

The Fermi function describes a non-monochromatic electron beam with a spread in energy $k_B T$. Convolution with $-\partial f(E, k_B T)/\partial E$ averages both the conductivity and density of states over a range in energy $k_B T$. Both $\sigma(E)$ and $N(E)$ can be obtained directly from the energy band diagram for a periodic potential, which is a solution to the Schrodinger equation.

The electron density at a given chemical potential μ we obtain by simply integrating the thermodynamic density of states.

$$n(\mu) = \int_{-\infty}^{\mu} N(\bar{E}, \hbar/\tau, k_B T) d\bar{E} \quad (3)$$

In the simplest picture, the device terminals directly control the electron density. A plot of conductivity versus electron density should then closely resemble the actual device I-V characteristic. If coupled with a semiclassical device simulator, it should be possible to obtain the exact device I-V curves.

In the grating-gate devices, x and y motion are decoupled except for the constraint that the total energy of motion is a constant. Thus, it is possible to express the conductance tensor and density-of-states in two dimensions as a convolution of various one dimensional quantities

$$\sigma_{xx}^{2D}(E) = \frac{1}{2} \sigma_{1D}^{xx} \otimes N_y(E) \quad (4)$$

$$\sigma_{yy}^{2D}(E) = \frac{1}{2} \sigma_{1D}^{yy} \otimes N_x(E) \quad (5)$$

$$N_{2D}(E) = \frac{1}{2} N_x(E) \otimes N_y(E) \quad (6)$$

where x is the superlattice direction and y is the free electron direction. This building up of the dimension of space by repeated convolutions cannot be done in the grid gate device, which is truly a two dimensional problem in which the x and y motions are not independent. These formulas give insight into how features in conductance disappear as we increase the dimensionality of the grating superlattice. They are gradually weakened by convolution with the free electron density of states. σ_{yy}^{2D} is identically zero for these devices.

The Q1D grating gate transistor depends on a modulation of its scattering time to show structure in conductance, whereas the main conductance modulation in the superlattice transistor is a result of the electron's Fermi group velocity tending to zero at a Brillouin zone boundary or zone center. Scattering between subbands is the important mechanism for observing a conductance modulation in the Q1D transistor. The scattering rate becomes very high as the Fermi level passes into a new subband and causes the conductance to fall dramatically. The formulas above also tell how closely the Q1D grating gate transistor approximates a Q1D wire. In the limit that the Fermi energy lies well below the top of the superlattice potential the approximation is very good.

Thus far we have only been able to make qualitative comparisons with experiments, though plan to make more quantitative comparisons by combining this theory with semiclassical device simulators. It also appears possible to make a combination of terminal voltages proportional to the electron density in Si devices, so that this theory can be compared directly with experiment without the need for involved device simulation.

D. List of Publications

1. K. Ismail, W. Chu, D.A. Antoniadis, and H.I. Smith, "Surface-Superlattice Effects in a Grating-Gate GaAs/GaAlAs Modulation-Doped Field-Effect Transistor," *Appl. Phys. Lett.*, 52, 1071 (1988).
2. K. Ismail, W. Chu, D.A. Antoniadis, and H.I. Smith, "Lateral-Surface Superlattice and Quasi-One Dimensional GaAs/GaAlAs MODFETs Fabricated Using X-Ray and Deep-UV Lithography," *J. Vac. Sci. Technol.*, 6, 1824 (1988).
3. K. Ismail, W. Chu, A. Yen, D.A. Antoniadis and H.I. Smith, "Negative Transconductance and Negative Differential Resistance in a Grid-Gate Modulation-Doped Field-Effect Transistor,": *Appl. Phys. Lett.* vol. 54, January 1989.
4. K. Ismail, D.A. Antoniadis, and H.I. Smith, "One-Dimensional Subbands and Mobility Modulation in GaAs/AlGaAs Quantum Wires," accepted for publication in *Appl. Phys. Lett.*
5. P.F. Bagwell, D.A. Antoniadis, and T.P. Orlando, "Quantum Mechanical and Nonstationary Transport Phenomena in Nanostructured Silicon Inversion Layers", in VLSI Electronics, Microstructure Science, Vol. 18, Advanced MOS Device Physics, N.G. Einspruch and G. Gildenblat Editors, Academic Press, San Diego, CA 1988.
6. P.F. Bagwell, and T.P. Orlando, "Broadened Conductivity Tensor and Density of States for a Superlattice in 1,2, and 3 Dimensions," accepted for publication , *Phys. Rev. B*.
7. P.F. Bagwell, and T.P. Orlando, "A Study of Landauer's Conductance Formula and its Generalization to Finite Voltages", submitted for publication, *Phys. Rev. B*.
8. D.A. Antoniadis, "Quantum Mechanical and Non-Steady-State Transport Phenomena in Nanostructured Silicon Inversion Layers," Extended Abstracts, 19th Conference on Solid State Devices and Materials, Aug. 25-27, 1987, The Japan Society of Applied Physics, Tokyo, Japan.
9. K. Ismail, W. Chu, D.A. Antoniadis, and H.I. Smith, "Superlattice Effect in A Grid-Gate GaAs/AlGaAs MODFET Structure," Conference on Gallium Arsenide and Related compounds, Atlanta, Georgia, Sept. 12-14, 1988.
10. A. Yen, "Grating Gate Si-MOSFET for study of Quantum Transport Effects", S.M. Thesis, Department of Electrical Engineering and Computer Science, MIT, August 1987.
11. P.F. Bagwell, "Quantum Mechanical Transport Phenomena in Nanostructured Inversion Layers", M.S. Thesis, Department of Electrical Engineering and computer Science, MIT, February 1988.
12. W. Chu, "Fabrication of Lateral-Surface-Superlattice MODFETs Using X-Ray Lithography," M.S. Thesis, Dept. of Electrical Engineering and Computer Science, MIT, September 1988.