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High Energy Electron Injection into Semiconductor Superlattices, Quantum Wells, and Quantum Wires

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The goal of this contract has been to investigate high energy injection of carriers into semiconductor multiple quantum well structures, superlattices, and quantum waveguide structures. Towards this goal, significant accomplishments have been obtained by the PI through a broad range of ongoing research efforts. To briefly summarize the accomplishments under this contract, focus will be given to four different research fronts to which the resources of the grant were expended: 1) Carrier relaxation during ultra-fast laser excitation in multiple quantum well structures, 2) Fabrication and characterization of resonant tunneling diodes, 3) Modeling and fabrication of quantum waveguide structures, and 4) Modeling and fabrication of a Superlattice Base Transistor. A summary the research results corresponding to these four areas are discussed below.

1) Hot Carrier Relaxation during Ultra-fast Optical Excitation

The PI has made a significant contribution to the modeling of ultra-fast carrier relaxation in quantum well structures, which has been recognized through a number of invited presentations, most notably the QELC conference in Baltimore, Md., 1989, and the HCIS-7 conference in Nara, Japan, 1991. In this research, we have applied Monte Carlo particle simulation techniques to the study of ultra-fast carrier relaxation using a full model of the electron and hole dynamics in a multi-subband quantum well system including such effects as nonequilibrium polar optical phonons and the effects of phonon confinement. We have collaborated closely with P. Lugli, at the II University of Rome in the theoretical modeling, and with D. Chemla, W. Knox and J. Shah at Bell labs, Holmdel for experimental results. Our simulations have elucidated several important aspects of hot carrier relaxation in such systems including: relaxation through carrier-carrier scattering[1-3], hot phonon effects on energy relaxation in quantum wells[4-6], surface roughness effects on lateral transport[7], and intersubband relaxation of carriers during photoexcitation in single and coupled quantum well systems[8-13]. A detailed review of our results in these various areas have been summarized in a soon to be published book on Hot Carriers in Nanostructures[14] edited by J. Shah of AT&T Bell Laboratories, Holmdel.

2) Fabrication and Characterization of Resonant Tunneling Diodes

Under the ONR contract, work was supported in the growth, fabrication, testing and modeling of resonant tunneling diodes (RTDs). Support was primarily for the research work of Hyungmo Yoo, a 1990 Ph.D graduate from our department, and involved close collaboration with J. Arthur at OSU and M. Reed at Texas Instruments in Richardson, Texas. Our primary concern in these studies was the effect of the so called 'spacer' layer in the transport properties of lattice matched AlGaAs/GaAs RTDs and pseudomorphic AlGaAs/InGaAs RTDs. Heretofore, relatively little was known about the effect of such a layer other than improved performance due to the minimization of dopant diffusion into the active tunneling region of the structure during MBE growth. Structures were grown using the MBE facility at Oregon State University with various spacer layer configurations and barrier thicknesses and then studied using high field magneto-transport (SdH) measurements to probe elastic and inelastic tunneling at 1.5 K. We have shown[15-18] that such undoped layers next to the tunneling structure play a crucial role in the formation of an accumulation layer next to the heterointerface, and that novel tunneling characteristics may be obtained through asymmetric placement of these layers on either side of the barriers. We established a certain directionality of outdiffusion of Si impurities during MBE growth from the relative effects of asymmetric spacer layers on the substrate versus top side of such devices. From these samples, and from samples obtained from the TI group, we also found oscillatory magneto-transport behavior due to both elastic impurity assisted tunneling, and LO phonon mediated inelastic tunneling, which corroborated results obtained by the Nottingham group on similar structures. At present, we are preparing a long article for submission to Physical Review publishing our full results related to this work.

3) Modeling and fabrication of quantum waveguide structures

A project undertaken in the most recent phase of the ONR contract has been the fabrication and modeling of quantum waveguide structures. This work has been performed in collaboration with Martin Wybourne at the University of Oregon(UO), and with V.K. Tripathi at Oregon State University, with additional support from Tektronix Research Laboratories in Beaverton, Oregon. This support has been in the form of a $100K, two year grant for the joint OSU/UO effort in addition to their key donations of the MBE and electron beam facilities currently in place.

In the theoretical modeling of such systems, we have attempted to make a close analogy to electromagnetic waveguide problems in order to utilize the enormous analytical and numerical techniques that have been developed in this field. In his Ph.D. work on this subject, Andreas Weisshaar[19-23] applied mode-matching techniques to the study of metallic waveguides, quantum waveguides, and optical waveguides. The most interesting results of these studies related to quantum waveguides were the effects of bend discontinuities on the transmission and conductance characteristics in split-gate structures[19,22], and the predictions of resonant tunneling and negative differential resistance in split gate, quantum dot structures[20,22,23]. In the latter case[22], a systematic method was presented for analyzing the resonance energies in terms of structural parameters which should be useful in optimizing experimentally realizable structures.

In parallel with the modeling effort, we have fabricated various split-gate structures using the MBE and processing facilities at OSU and the electon beam lithography laboratory at the University of Oregon. Modulation doped heterojunction layers were grown both at OSU and at Tektronix using MBE, which were fabricated using optical lithography to realize split-gate FET structures in the clean room facility at OSU[25]. These samples were then taken to the UO where fine structure split-gate (or point contact) structures were defined using the electron-beam lithography facility. An Oxford Instruments He3 dilution refrigerator with a 7 T superconducting magnet was used to perform precision conductance and I-V measurements at temperatures as low as 50 mK. The results of this work were presented at the 1991 NANOMES conference in Sante Fe, New Mexico (as an invited talk)[27] and the initial results have been published as well[26]. There we have shown what we believe to be resonance phenomena due to the cavity of a double bend, which appears as quasi-periodic structure in the conductance versus gate voltage. Subsequent measurements which verify these results on other structures are presently being prepared for publication.

4) Modeling and fabrication of a Superlattice Base Transistor

Considerable effort was expended on the design, fabrication, and modeling of a superlattice base transistor which would utilize resonant transport in continuum states in order to achieve higher gain in a conventional Hot Electron Transistor (HET) structure. Much of this work was performed by Jenifer Lary as part of her Ph.D dissertation[28]. Fabrication of such a transistor has proved difficult due to the inherent problem in unipolar HET structures of insuring that the base is not shorted to the collector or emitter. Our first devices, although showing common emitter and common base transistor characteristics, exhibited large base resistance effects due to the thin base and the large contact spacings which were used. A second mask set was designed in which guard rings and interdigitated base stripe geometries were introduced to minimize base spreading resistance effects. However, up to the present time, we have not succeeded in fabricating useful devices which are free from shorting effects in the base-collector characteristics. Bipolar superlattice base transistors were grown at OSU and fabricated at Tektronix using their standard HBT process. However, no significant performance improvement was found between a superlattice base device, and a non-superlattice base device of the same structural parameters. At present, one Master's candidate (Andrew Choo) is continuing the work on the unipolar device, although a similar structure has subsequently been reported 1989 at the HCIS-6 conference in Tempe, Arizona by English and coworkers at Bellcore.

A Monte Carlo simulation was developed for analyzing the transfer ratio of high energy injected carriers into the superlattice base[28]. A full superlattice Monte Carlo simulation program was written which included LO-phonon, impurity, intervalley, and intercarrier scattering for the minband states a superlattice, which allows a continuous transition from quasi-2D behavior in low lying bound states, to quasi-3D behavior in the continuum states above the barriers. To our knowledge, this is the first such particle simulation ever written which fully contains the superlattice states in both the scattering rates and the group velocity. An analysis of the expected performance of the superlattice base FET was undertaken with interesting results. The prediction of reduced scattering rates due to the formation of minibands was born out in the simulated results. However, due to the reduced group velocity in the minibands, shorter mean free paths were obtained, and subsequently reduced performance is predicted compared to a nonsuperlattice base. We are presently writing a paper for publication over this work, and it has been submitted to the upcoming SPIE meeting in March, 1992.

Publications Resulting from Work Performed under the ONR Contract

1. S.M. Goodnick and P. Lugli, "The Effect of Electron-Electron Scattering on Nonequilibrium Transport in Quantum Well Systems," *Phys. Rev. B* **37**, 2578 (1988).

2. S.M. Goodnick and P. Lugli, "The Influence of Electron-Hole Scattering on Subpicosecond Carrier Relaxation in AlGaAs/GaAs Quantum Wells," *Phys. Rev. B* **38**, 10135 (1988).

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13. S.M. Goodnick, J. Lary and P. Lugli, "Intersubband Relaxation of Hot Carriers in Quantum Well Systems," to be published in *Superlattices and Microstructures* .

14. S.M. Goodnick and P. Lugli, "Hot Carrier Relaxation in Quasi-2D Systems," in *Hot Carriers in Semiconductor Nanostructures: Physics and Applications*, (J. Shah, ed.), Academic Press Inc., pp. 191-234 (1992).

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28. J. Lary, "Electron Transport in Semiconductor Superlattices," Ph.D. dissertation, Oregon State University, 1991.

Graduate Students Supported under the CRP (until July 31, 1991)

Andreas Weisshaar, Ph.D. (May 1991), Modeling of quantum waveguides (also supported by V.K. Tripathi under the MMIC program). Presently a post-doctoral research associate supported under the Tektronix grant.

Jenifer Lary, Ph.D. (May 1991), MBE growth, device fabrication, Monte Carlo modeling of high field transport in semiconductor superlattices. (primarily supported by IBM fellowship).

Hyungmo Yoo, Ph.D. (June, 1990), MBE growth, device fabrication, magneto-transport measurements, device modeling (stipend primarily provided by J.R. Arthur through the Tektronix Chair).

Andrew Choo, M.S. candidate (7/1/90 to present), Fabrication of superlattice base hot electron transistor.

Alan Chin, M.S. candidate (9/31/90-6/1/91), Modeling of quantum waveguide structures(also supported by Textronix grant).

Wipawan Yindeepol, M.S. (July, 1990), Fabrication and testing of Modulation doped field effect transistor structures.

W. Gazelely, M.S. (Summer, 1989), Fabrication and testing of superlattice base transistor structure.