Electron-Phonon Interaction, Transport and Ultrafast Processes in Semiconductor Microstructures

Dr. Sankar Das Sarma
Professor of Physics

University of Maryland
College Park, MD 20742

Final Report on Grant No. 01528547

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

We have fulfilled our contract obligations completely by doing theoretical research on electron-phonon interaction and transport properties in submicron semiconductor structures with the emphasis on ultrafast processes and many-body effects. Fifty-five papers have been published based on our research during the contract period.

Approved for public release; distribution unlimited.

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UL

10

12b. DISTRIBUTION CODE

12a. DISTRIBUTION/AVAILABILITY STATEMENT

13. ABSTRACT (Maximum 200 words)

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED
ELECTRON-PHONON INTERACTION, TRANSPORT AND ULTRAFAST PROCESSES IN SEMICONDUCTOR MICROSTRUCTURES

FINAL REPORT
1989-1992

Sankar Das Sarma
Professor of Physics

August 14, 1992

U.S. Army Research Office

Contract No. DAAL03-89-K-0026
ARO Proposal Number 26278-EL

University of Maryland
College Park, MD 20742

Approved for Public Release
Distribution Unlimited

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.
Final Report on ARO Contract Number DAAL03-89-K-0026

During the last six years we have published (or, had accepted for publication) one hundred (100) papers in refereed journals (including many invited papers in international conferences, invited reviews and book chapters) under ARO support. We have had sixty (60) refereed publications under ARO sponsorship so far during the current three-year contract period. In addition, there are currently about half a dozen papers which have either been submitted for publication (or, will soon be submitted). A publication list is provided at the end of this section.

During the current three year contract period we have had thirty (30) invited papers, session chairmanship, etc. in international conferences for work done under ARO sponsorship. In addition, we gave a large number (~20) of invited seminars, colloquia and lectures at various universities and research laboratories on our research. We made over forty (40) scientific presentations at international conferences (including APS March meetings) on work related to the current ARO contract. Among our invited papers are two at the Hot Electron Conferences, two at the APS March meetings, two at NATO school on nanostructures, one at the IEEE meeting, several at SPIE meetings, and, a number of invited talks at specialized workshops (held by DoD agencies such as ONR) on nanostructures and ultrafast processes. We contributed an invited chapter on many-body effects to the recent book of reviews on hot carrier physics and applications in nanostructures which is edited by J. Shah of AT&T and published by the Academic Press. We published ten (10) invited reviews on work done under ARO sponsorship. Of these, four invited reviews are book chapters in recently published books on nanostructures.

Three postdoctoral research associates partially supported by our ARO contract have gone on to obtain tenure-track assistant professorship positions in physics departments of major research universities. The five graduate students who did their PhD research under the sponsorship of this contract have all gone on to excellent postdoctoral positions. We provide a personnel list at the end of this
The PI, Sankar Das Sarma, has been awarded a Distinguished Research Fellowship for nanostructure research by the Graduate School of the University of Maryland for the 1991-92 academic year. (This is the highest research honor awarded by the university.) He is a member of the Organizing Committee for 10th International Conference on Electronic Properties of Two Dimensional Systems (to be held in Newport, Rhode Island in June of 1993), which is considered to be the premier conference on the physics of nanostructures. Das Sarma has been awarded the Gordon Godfrey Bequest Visiting Professorship by the University of New South Wales, Australia where he will give a series of lectures on the physics of nanostructures during the summer of 1992. Earlier, in 1988-89 he was awarded a Royal Society Visiting Professorship and Fellowship to the Cavendish Laboratory (Cambridge University) by the British Royal Society. In 1988, Das Sarma was also one of the ten scientists invited to the Soviet Union by the Soviet Academy of Sciences as a part of US - Soviet bilateral scientific exchange program in low-dimensional electron systems.

Following is a very brief summary of some of the highlights of our research accomplishment under the current ARO support.

1. Many-body effects in hot electron relaxation.

Our detailed theory, within the electron temperature and the hot phonon model, essentially completely solves the problem of picosecond hot electron relaxation via LO-phonon emission in two dimensional nanostructures. Our theory includes quantum subband structure, quantum degeneracy, dynamical screening, plasmon-phonon coupling, quasiparticle-phonon coupling induced phonon self-energy correction, slab and interface phonon modes, and, hot phonon bottleneck effect. We get good agreement with the available experimental results and explain the low temperature "missing loss" mechanism as that due to quasiparticle-phonon coupling.
2. Inelastic scattering in ballistic transistors

We have developed a many-body theory, which includes Coulomb electron-electron and Fröhlich electron-phonon interactions on an equal footing for the first time, for inelastic processes in ballistic hot electron transistors (e.g., THETA devices), calculating energy-, doping density-, and, temperature- dependence of the ballistic electron inelastic mean free path in the base region. Our theory considers both two dimensional and three dimensional systems, corresponding respectively to lateral and vertical motion through the base region.

3. Band gap and effective mass renormalization

We have obtained the exchange-correlation induced band gap and effective mass renormalization in two and three dimensional semiconductor structures, including both electron-electron and electron-phonon interaction effects. Our results are in excellent agreement with the available experimental data.

4. Scattering effects on resonant tunneling in nanostructures

We developed a microscopic theory for the impurity scattering effect on the resonant tunneling current through a double-barrier-single-quantum-well structure, showing that disorder can produce conductance fluctuation- and weak localization-type structure on the tunneling current spectra. Our microscopic theory also provides a justification for the Breit-Wigner type phenomenological formula used in the literature.

5. Vertical miniband transport in superlattices

We have developed a detailed Bloch type theory, based on the Kubo formula, for vertical transport through minibands in superlattices. Our theory explains a number of puzzling experimental results in superlattice miniband transport.

6. Electronic structure of nanostructures

We have developed a self-consistent theory (including exchange-correlation effects) for calculating the electronic structure of parabolic semiconductor quantum wells, both with and without an external magnetic field. Our numerical
results are in good agreement with spectroscopic and transport data. We also developed a theory for the shallow impurity donor levels in GaAs quantum wells by exactly solving the Schrödinger's equation in the whole system (i.e., including the barrier).

7. **Transport properties of high electron mobility nanostructures**

We have developed a comprehensive theory for the electronic mobility of a high mobility modulation-doped GaAs heterojunction by solving the Boltzmann integral equation exactly numerically through an iterative procedure. Our theory includes all relevant phonon scattering processes. Our calculation includes finite temperature and dynamical screening effects, and shows that the highest achievable mobility in a GaAs heterojunction to be about $4 \times 10^6$ cm$^2$/v/s at 10 K and about $4 \times 10^7$ cm$^2$/v/s at 1 K. We also explained the recently observed density dependent maximum in the temperature dependence of low temperature mobility as a competition between screening and deformation potential matrix element effect.

8. **Optical properties of quantum dots and wires**

We have carried out some preliminary calculations of optical properties of quantum wires and dots. Our theory for the quantum wire collective plasmon spectra has recently been verified by a Raman scattering experiment.

9. **Inelastic processes in quantum wires**

We have shown that, due to very strict restrictions imposed by energy-momentum conservation in one dimension, inelastic scattering is highly constrained in quantum wires, leading to a very sharp plasmon emission threshold. This phenomenon should lead to a strong negative differential resistance and we have proposed a device based on this (Appendix A).

10. **Electron-phonon coupling in quantum wires**

We have developed a detailed theory for electron-phonon coupling in semiconductor quantum wires, including slab phonon and dynamical screening effects. We have applied our theory to the carrier energy relaxation problem in quantum wires (Appendix B).
In the following we provide a list of our publications (during the last three years) under the current ARO support and some other relevant information.

**Publications (under the current ARO contract)**


34. Electronic Structure, Density Scaling, and, Optical Properties of Parabolic and Square Quantum Wells (M. P. Stopa and S. Das Sarma), Phys. Rev. B.


Invited Talks at International Conferences (the last 3 years)


2. Chair, Session on Quantum Hall Effect, APS March Meeting (St. Louis, March 1989).

3. Chair, Session on Many-Body Effects, APS March Meeting (St. Louis, March 1989).

4. Invited Speaker, Kathmandu Summer School on Theoretical Physics (Nepal, Summer 1989); "Unusual Solutions to the Usual Schrödinger's Equation."

5. Invited Talk, International Symposium on Surface Waves in Solids and Layered Structures (Bulgaria, Summer 1989); "Collective Excitations in Structured Low Dimensional Systems."

6. Invited Talk, 36th Annual AVS Symposium (Boston, October 1989) "Non-equilibrium Crystal Growth".


8. Invited Plenary Lecturer, Brazilian Summer School on Low Dimensional Systems (Sao Carlos, Brazil, February 1990).
9. Invited Speaker, NATO Workshop on "Light Scattering in Semiconductors" (Canada, March 1990); "Excitations and Mode Coupling a Doped Polar System."


12. Chair, Session on Transport in Microstructures, APS March Meeting (Anaheim, March 1990).

13. Invited Speaker, NATO Workshop on "Transport in Microstructures" (Turkey, April 1990).

14. Chair, Quantum Transport Session, Workshop on Computational Electronics (Univ. of Illinois, May 1990).

15. Invited Speaker, Winter School on Theoretical Physics (Brasilia, Brazil, July 1990).


27. Invited Speaker, International Workshop on Disorder (Hyderabad, India, December 1991).


32. Invited Talk, APS March Meeting (Indianapolis, March 1991); "Quantum Hall Effect in Double Quantum Well Systems".


34. Invited Visitor, Workshop on Quantum Phase Transitions, ITP, Univ. of California, Santa Barbara (Spring-Summer 1992).

35. Chair, One Dimensional Systems, APS March Meeting (March 1992).

36. Invited Talk, European Science Foundation Conference on Kinetics of Epitaxial Growth (Davos Platz, Switzerland, Summer, 1992).

Personnel (at least partially) supported by ARO (last 3 years)

Graduate students:
1) R. Jalabert (PhD 1989), IBM postdoctoral fellow at Yale University.
2) M. P. Stopa (PhD 1990), staff research scientist at NTT Basic Sciences Laboratory, Tokyo.
3) Song He (PhD 1991), postdoctoral research associate at the Theory Group, AT&T Bell Laboratory.
4) T. Kawamura (PhD 1991), postdoctoral research associate at the Coordinated Sciences Laboratory, University of Illinois, Urbana-Champaign.
5) I. K. Marmorkos (PhD 1991) research scientist at the Lorenz Theory Institute, University of Leiden, Netherlands.

Research associates:
1) J. K. Jain, currently a tenure-track assistant professor at the physics department of SUNY, Stony Brook.
2) X. C. Xie, currently a tenure-track assistant professor at the physics department of Oklahoma State University.
3) H. A. Fertig, currently a tenure-track assistant professor at the physics department of University of Kentucky.
4) Y. K. (Ben) Hu, currently at Maryland.