Final Report on NASA Ames - Rice University JRI Project

"Technology Development of Miniaturized Far-Infrared Sources for Biomolecular Spectroscopy"

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The objective of this project was to develop a purely solid-state based, thus miniaturized, far-infrared (FIR) (also known as terahertz (THz)) wave source using III-V semiconductor nanostructures for biomolecular detection and sensing. Many biomolecules, such as DNA and proteins, have distinct spectroscopic features in the FIR wavelength range as a result of vibration-rotation-tunneling motions and various inter- and intra-molecule collective motions. Spectroscopic characterization of such molecules requires narrow linewidth, sufficiently high power, tunable (in wavelength), and coherent FIR sources. Unfortunately, the FIR frequency is one of the least technologically developed ranges in the electromagnetic spectrum. Currently available FIR sources based on non-solid state technology are bulky, inefficient, and very often incoherent.

In this project we investigated antimonide based compound semiconductor (ABCS) nanostructures as the active medium to generate FIR radiation. The final goal of this project was to demonstrate a semiconductor THz source integrated with a pumping diode laser module to achieve a compact system for biomolecular applications.

Major accomplishments are summarized below:

1) We grew high-quality InAs quantum wells with AlSb barriers with well widths ranging from 2 nm to 10 nm and observed intersubband transitions (ISBTs) in all samples and photoluminescence in narrow wells. We then systematically studied the ISBT energy, intensity, and linewidth vs. well width and temperature and compared with theory. The results were published in *Applied Physics Letters*.

2) We also grew coupled double quantum wells and observed THz splitting in ISBTs in the coupled wells, whose magnitude was consistent with theoretical simulations.

3) We obtained THz quantum cascade lasers from the University of Neuchatel and used them for cyclotron resonance studies of ABCS structures. This work represents the first successful spectroscopic application of THz quantum cascade lasers and was published in *Optics Letters*.

4) Extensive computer modeling capabilities have been developed for narrow band semiconductors, including the antimonide quantum wells and superlattices. These capabilities are centered on the 8-band k.p band structure theory based on envelope function approximations. A set of finite-difference-based numerical computer simulation programs was developed and tested extensively. This set of programs now forms the basic tools for antimonide-based quantum well designs. The programs can deal with self-consistent coupling of Schroedinger equations with Poisson equations and are very generic and flexible to deal with a variety of heterostructures.

5) Close interactions between the experiments and theoretical modeling have been established and resulted in significant progress in the understanding of electronic and optical properties of antimonide-based semiconductor structures. This understanding includes optical absorption spectra of InAs/AlSb quantum wells as well as the parameter-dependence of absorption spectrum.

6) The project has resulted in publication of journal papers and conference presentations listed in the following. As part of the report, the publications are attached.

Publications:

1. D. C. Larrabee, G. A. Khodaparast, F. K. Tittel, J. Kono, M. Rochat, L. Ajili, J. Faist, H. Beere, E. Linfield, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, S. J. Chung, and M. B. Santos, "Application of Terahertz Quantum

Cascade Lasers to Semiconductor Cyclotron Resonance," *Optics Letters* **29**, 122 (2004).

2. J. Li, K. I. Kolokolov, C. Z. Ning, D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, S. Sasa, and M. Inoue, "Intersubband Transitions in InAs/AlSb Quantum Wells" (invited paper), in: *MRS Proceedings Volume 744, Progress in Semiconductors II – Electronics and Optoelectronic Applications*, edited by B. D. Weaver, M. O. Manasreh, C. C. Jagadish, and S. Zollner (Materials Research Society, 2003), pp. M9.2.1-M9.2.12.

3. D. C. Larrabee, J. Tang, M. Liang, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, O. Suekane, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband transitions in narrow InAs/AlSb quantum wells," in: *Proceedings of the 26th International Conference on the Physics of Semiconductors*, edited by A. R. Long and J. H. Davies (Institute of Physics Publishing, Bristol, 2003), P129.

4. K. Kolokolov, J. Li, and C. Z. Ning, "k·p Hamiltonian without spurious-state solutions," Phys. Rev. B **68**, 161308 (2003).

5. K. Kolokolov and C. Z. Ning, "Doping-induced type-II to type-I transitions and interband optical gain in InAs/AlSb quantum wells," Appl. Phys. Lett. **83**, 1581 (2003).

6. J. Li, K. I. Kolokolov, C. Z. Ning, D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, S. Sasa, and M. Inoue, "Microscopic Modeling of Intersubband Resonances in InAs/AlSb Quantum Wells," *Physica E*, in press.

7. D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Temperature Dependence of Intersubband Transitions in InAs/AlSb Quantum Wells," Appl. Phys. Lett. **83**, 3936 (2003).

Presentations:

1. D. C. Larrabee, G. A. Khodaparast, F. K. Tittel, J. Kono, M. Rochat, L. Ajili, J. Faist, H. Beere, E. Linfield, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, S. J. Chung, and M. B. Santos, "Application of Terahertz Quantum Cascade Lasers to Semiconductor Cyclotron Resonance" (poster), the 11th IEEE International Conference on Terahertz Electronics (THz 2003), Sendai, Japan, September 24-26, 2003.

2. D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband Transitions in Narrow InAs/AlSb Quantum Wells" (poster), the 7th International Conference on Intersubband Transitions in Quantum Wells (ITQW 2003), Evolene, Switzerland, September 1-5, 2003.

3. Y. Nakajima, M. Nakai, K. Ueda, S. Sasa, M. Inoue, D. C. Larrabee, G. A. Khodaparast, J. Kono, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband and interband transitions in InAs/AlSb multiple quantum wells" (poster), the 13th International Conference on Nonequilibrium Carrier Dynamics in Semiconductors (HCIS-13), Modena, Italy, July 28 – August 1, 2003.

4. S. Sasa, K. Ueda, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, D. C. Larrabee, G. A. Khodaparast, J. Kono, K. I. Kolokolov, J. Li, and C. Z. Ning "Intersubband Transitions in Coupled InAs/AlSb Quantum Wells" (poster), the 11th International Conference on Narrow Gap Semiconductors (NGS-11), Buffalo, New York, June 16-20, 2003.

5. D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband Transitions in Narrow InAs/AlSb Quantum Wells" (poster), the 11th International Conference on Narrow Gap Semiconductors (NGS-11), Buffalo, New York, June 16-20, 2003.

6. S. M. Crankshaw, D. C. Larrabee, G. A. Khodaparast, J. Kono, Y. Nakajima, K. Ueda, S. Sasa, and M. Inoue, "Magneto-Transport of

Antimonide-Based Compound Semiconductor Structures" (poster), the 2003 March Meeting of the American Physical Society, Austin, Texas, March 3-7, 2003.

7. D. C. Larrabee, M. Liang, S. M. Crankshaw, J. Tang, G. A. Khodaparast, J. Kono, Y. Nakajima, K. Ueda, O. Suekane, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband Transitions in Narrow InAs/AlSb Quantum Wells" (oral), the 2003 March Meeting of the American Physical Society, Austin, Texas, March 3-7, 2003.

8. J. Tang, D. C. Larrabee, B. E. Brinson, G. A. Khodaparast, J. Kono, Y. Nakajima, K. Ueda, O. Suekane, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Evaluation of interfaces in narrow InAs/AlSb quantum wells" (poster), the 1st IEEE Lester Eastman Conference on High Performance Devices, Newark, Delaware, August 6-8, 2002.

9. D. C. Larrabee, J. Tang, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, O. Suekane, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband transitions in narrow InAs/AlSb quantum wells" (oral), the 1st IEEE Lester Eastman Conference on High Performance Devices, Newark, Delaware, August 6-8, 2002.

10. D. C. Larrabee, J. Tang, M. Liang, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, O. Suekane, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband transitions in narrow InAs/AlSb quantum wells" (poster), the 26th International Conference on the Physics of Semiconductors (ICPS 26), Edinburgh, UK, July 29 to August 2, 2002.

11. J. Tang, D. C. Larrabee, G. A. Khodaparast, J. Kono, M. Karasaki, K. Ueda, S. Sasa, M. Inoue, K. I. Kolokolov, and C. Z. Ning, "Intersubband transitions in narrow InAs/AlSb quantum wells" (poster), 2002 March Meeting of the American Physical Society, Indianapolis, Indiana, March 18-22, 2002.

12. A. Liu, J. Li, C.-Z. Ning, D. C. Larrabee, J. Tang, G. A. Khodaparast, J. Kono, S. Sasa, and M. Inoue, "Intersubband THz generation in Sb-based quantum wells pumped by near-infrared diode lasers" (poster), the 6th International Conference on Intersubband Transitions in Quantum Wells (ITQW'01), Asilomar, California, September 10-14, 2001.

13. A. Liu, J. Li, C. Z. Ning, D. C. Larrabee, J. Tang, G. A. Khodaparast, J. Kono, S. Sasa, and M Inoue, "Far-infrared generation in Sb-based quantum wells pumped by near-infrared laser diodes" (poster), the 3rd Workshop on the Fabrication, Characterization, and Applications of 6.1 Å III-V Semiconductors, Snowbird, Utah, July 31 – August 2, 2001.