Final Report for Period: 08/2006 - 07/2007
Submitted on: 11/15/2007
Principal Investigator: Citrin, David S.
Award ID: 0305524
Organization: GA Tech Res Corp - GIT
Title:
Intersubband Dynamics in Semiconductor Quantum Wells

Project Participants

Senior Personnel

Name: Citrin, David
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Hong, Shih-Hsuan
Worked for more than 160 Hours: Yes
Contribution to Project:
S.-H. Hong is studying theoretically dyanmical aspects of mid-infrared quantum-cascade lasers. In particular, he studies mode locking and noise aspeccts.

Name: Kurt, Hamza
Worked for more than 160 Hours: Yes
Contribution to Project:
H. Kurt has written finite-difference time-domain code to treat far-infrared propagation in photnic-bandgap structures. He is exploring the use of such structures to enhance the interaction of far-infrared electromagnetic fields with intersubband transitions in quantum wells.

Name: Kim, Dong Kwon
Worked for more than 160 Hours: Yes
Contribution to Project:
Mr Kim is carrying out research on the optimal design of asymmetric double quantum wells for low-voltage electroabsorption modulators. These designs will serve as the starting point to study THz-modulated quantum wells exhibiting strongly enhanced optical-THz nondegenerate nonlinearities.

Name: Bai, Jing
Worked for more than 160 Hours: Yes
Contribution to Project:
Jing worked on intracavity nonlinearities in mid-infrared quantum cascade lasers. In such lasers, electrons cascade down successive periods of the structure between conduction subbands. Jing worked on multiply resonant structures which support significant harmonic generation. Jing worked on optimized design of quantum cascade lasers for such nonlinearities based on the technique of aupersymmetric quantum mechanics. Jing graduates with a PhD in summer 2007 and has secured a faculty position in the Department of Electrical Engineering at the University of Minnnesota, Duluth.

Name: Backes, Thomas
Worked for more than 160 Hours: Yes
Contribution to Project:
Mr Backes is working on the use of plasmonic structures for the mirrors in intersubband lasers (quantum casdcade lasers). Currently, he is working on the plasmon-polariton dispersion of two-dimensional nanoparticle arrays.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

University of California-Santa Barbara

This involved collaborative work with Prof. Mark Sherwin of the Department of Physics at UCSB, Dr. Sam Carter of JILA, and Dr. Alexey Maslov of NASA Ames, and culminated in the publication

S. G. Carter, V. Birkedal, C. S. Wang, L. A. Coldren, A. V. Maslov, D. S. Citrin, and M. S. Sherwin, 'Quantum coherence in an Optical Modulator,' Science, vol. 310, pp. 651-653, 2005.

University of Colorado at Boulder

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NASA Ames Research Center

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Other Collaborators or Contacts

Prof. Mark S. Sherwin, Department of Physics, UCSB. Carries out optical spectroscopy of quantum wells in far-infrared fields.

Dr. V. Cuilin, Department of Physics, UCSB. Post-doc of M. S. Sherwin.

Dr. Alex Maslov, NASA Ames, Moffett Field, CA. Ex Ph.D. student and post-doc who works with PI in analysing experimental data from the group of M. S. Sherwin. Presently, research scientist with Canon.

Dr. Adriano Batista, University of Brasilia, Brazil. Ex post-doc. Collaborates on far-infrared dynamics of intersubband transitions.

Prof. Pablo Tamborenea, University of Buenos Aires, Argentina. Collaborates on far-infrared dynamics of intersubband transitions. Presently with the Brazilian patent office.

Prof. Martin Koch, Technical University of Braunschweig. THz source development.

Prof. Stephen Ralph, Georgia Insititute of Technology. THz source development.

Dr. Doug Denison, Georgia Tech Research Institute. THz source development.

Activities and Findings

Research and Education Activities:

The computational techniques for the nonlinear intersubband response of wide n-type quantum wells to strong far-infrared fields developed by the PI and ex post-doc and collaborator A. Batista were extended to include propagation effects of the electromagnetic field and to account for temporally shaped far-infrared pulses.

Subsequently, we have been studying the interaction of radio-frequency fields and intrinsic quantum wells probed optically. Work has begun on the optimization of quantum-well design to maximize the electric-field sensativity of the optical properties.

During 8/05-8/06 the PI spent considerable time at Georgia Tech Lorraine in Metz, France -- Georgia Tech's campus in Europe. During that time, then PhD student Hamza Kurt, who has also been supported by the program, carried out research in an international environment, wrote his thesis, and ultimately earned his PhD. Dr. Kurt was subsequently a post-doctoral research fellow at Ecole Polytechnique in France. He has now secured a faculty position at a university in Turkey.

Findings:

This work led to a publication in Optical Letters and a publication in Physical Review Letters. For the former, we showed theoretically, that far-infrared nonlinearities of quantum wells (in this case bistability) can be enhanced significantly in an optical-resonator structure. For the later, we showed theoretically that in order to produce well defined intersubband Rabi flopping in wide n-type quantum wells, it is necessary to shape temporally the far-infrared pulse so that the carrier frequency tracks the dynamic renormalization of the intersubband splitting.

Also supported in part by this program is S. G. Carter, V. Birkedal, C. S. Wang, L. A. Coldren, A. V. Maslov, D. S. Citrin, and M. S. Sherwin, 'Quantum coherence in an Optical Modulator,' Science, vol. 310, pp. 651-653, 2005, in which the excitonic Autler-Townes splitting in an interband optical transition in a quantum well -- a precursor to electromagnetic induced transparency -- in a strong THz field was observed and modeled. This is a fundamental coherent optical effect involving a three-level system that had never before been observed where two of the levels are confined states in a quantum well.

Part of the program is to find ways to enhance the effect of strongly modulating a quantum well on an intersubband transition (at THz frequencies) on the optical properties. To this end, the program has partially supported work on THz photonic crystals. This work emphasized ways to control the THz properties of such structures using photonic crystal waveguides and other novel photonic crystal based structures.

Training and Development:

Three graduate students have been partially supported by the project. They are studying intersubband dynamics in quantum wells and ways to enhance these nonlinear properties, for example using photonic crystals, for possible applications.

One student partially supported by the program, Hamza Kurt, earned his PhD in 8/06.

Outreach Activities:

My collaboration with Dr. A. Batista (Univ. of Brasilia) and Prof. P. Tamborenea (Univ. of Buenos Aires) provided impetus for me to participate in a US DOE funded professional development program in Latin America (CIBER-MERCOSUR program run by Florida International University). Not only were technical discusions with P. Tamborenea carried out in Buenos Aires, but professional contacts were made at the University of Chile in Santiago.

As a result of these contacts, the PI awarded a Fulbright Fellowship to carry out lecturing and collaborative research at the University of Brasilia. Unfortunately, due to scheduling conflicts, he had to decline the offer.

During 8/05-8/06 the PI spent a considerable portion of his time at Georgia Tech Lorraine in Metz, France. Research funded under the program was carried out during his stay there. This work also served to provide materials for a module in his special topics graduate course given there on Nano-optics.

Journal Publications

A. A. Batista and D. S. Citrin, "Rabi flopping in a two-level system with a time-dependent energy renormalization: Intersubband transitions in quantum wells", Physical Review Letters, p. 127404, vol. 92, (2004). Published,

A. A. Batista and D. S. Citrin, "Enhanced terahertz bistability in a nonlinear Fabry-Perot resonator", Optics Letters, p. 367, vol. 29, (2004). Published,

Dae Sin Kim and D.S. Citrin, "Enhancement of terahertz radiation from photoconductors by elliptically-focused excitation", Applied Physics Letters, p. , vol. , ( ). Accepted,

Hamza Kurt, D. S. Citrin, "Photonic crystals for biochemical sensing in the terahertz region", Applied Physics Letters, p. 041108, vol. 87, (2005). Published,

Hamza Kurt and D. S. Citrin, "Coupled-resonator optical waveguides for biochemical sensing of picoliter volumes of analyte in the terahertz region", Applied Physics Letters, p. 241119, vol. 87, (2005). Published,

S. G. Carter, V. Birkedal, C. S. Wang, L. A. Coldren, A. V. Maslov, D. S. Citrin, and M. S. Sherwin, "Quantum coherence in an Optical Modulator", Science, p. 651, vol. 310, (2005). Published,

H. Kurt and D. S. Citrin, "Annular Photonic Crystals", Optics Express, p. 10316, vol. 13, (2005). Published,

D. S. Citrin and A. V. Maslov, "Interband optical spectra of magnetoexcitons in semiconductor nanorings: Electron-hole spatial correlation", Physical Review B, p. 073302, vol. 72, (2005). Published,

J. Bai and D. S. Citrin, "Supersymmetric Optimization of Second-harmonic Generation in Mid-infrared Quantum Cascade Lasers", Optics Express, p. 4043, vol. 14, (2006). Published,

H. Kurt and D. S. Citrin, "Photonic-crystal heterostructure waveguides", IEEE Journal of Quantum Electronics, p. , vol. , ( ). Accepted,

A. A. Batista and D. S. Citrin, "Quantum control with linear chirp in two-subband n-type quantum wells", Physical Review B, p. , vol. , ( ). Accepted,

T. Hasek, H. Kurt, D. S. Citrin, and M. Koch, "Photonic crystals for fluid sensing in the sub-terahertz range", Applied Physics Letters, p. 173508, vol. 89, (2006). Published,

D. S. Citrin, "Plasmon polaritons in finite-length metal-nanoparticle chains: the role of chain length unravelled", Nano Letters, p. 985, vol. 5, (2005). Published,

D. S. Citrin, "Subwavelength nanoplasmonic ring resonator", Journal of the Optical Society of America B, p. 1763, vol. 22, (2005). Published,

D. S. Citrin, "Plasmon-polariton transport in metal-nanoparticle chains embedded in a gain medium", Optics Letters, p. 98, vol. 31, (2006). Published,

D. S. Kim and D. S. Citrin, "Enhancement of terahertz radiation from photoconductors", Applied Physics Letters, p. 61108, vol. 87, (2005). Published,

D. S. Kim and D. S. Citrin, "Coulomb and radiation screening in photoconductive terahertz sources", Applied Physics Letters, p. 161117, vol. 88, (2006). Published,

D. K. Kim and D. S. Citrin, "Optimized asymmetric double quantum well for high electric-field-sensitiviity electroabsorption: excitonic mixing effects", IEEE Journal of Quantum Electronics, p. 651, vol. 43, (2007). Published,

D. K. Kim and D. S. Citrin, "Electrooptic properties of InGaAsP asymmetric double quantum wells: enhancement of slope efficiency in waveguide electroabsorption modulators", IEEE Journal of Quantum Electronics, p. 651, vol. 43, (2007). Published,

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

The article in Physical Review Letters (vol. 92, p. 127404, 2004) presents a nontrivial theoretical demonstration of strong-field coherent control in a semiconductor quantum well. These are typically difficult problems; the model system provided by wide n-type quantum wells subjected to intense far-infrared pulses is an ideal tractible system.

The paper published in Science (vol. 310, p. 651, 2005) demonstrates for the first time the excitonic Autler-Townes splitting in a THz modulated quantum well. This can be thought of as a THz-frequency optical modulator. In other words, this research pushes the limits of current high-speed optical modulators to probe their fundamental limits. Moreover, the work presents a fundamental coherent optical effect that also has potential implications for quantum optics in quantum wells and perhaps for future semiconductor-based quantum logic gates.

The work of D. K. Kim and D. S. Citrin outlines the effects of valence-band mixing and excitonic coupling on the electroabsorption of asymmetric double quantum wells. These effects have not hitherto been considered in this context. It was found that in suitably designed asymmetric double quantum wells that large changes in the optical absorption with small changes in electric field could be achieved, even when accounting for various broadening mechanisms at room temperature. This, in turn, led to designs of low-voltage electroabsorption modulators and high-slope-efficiency electroabsorption modulators, i.e., optical modulators in which a small voltage change can lead to a large change in the optical properties.

Under the program a series of papers in THz photonic crystals were published. The ultimate aim is to enhance effects discussed in the previous point, but the ostensible purpose was to explore ways to enable biochemical sensing in the THz regime.

Contributions to Other Disciplines:

The contribution of Phys. Rev. Lett. vol. 92, p. 127404, 2004 is an example of strong-field coherent control. The tractible model we have found may find interest in atomic physics as well as ultrafast chemistry.

The Science publication may have impact in quantum information science as it demonstrates a fundamental coherent optical process in quantum wells.

The work on the electrooptic effect in asymmetric double quantum wells may lead to low-voltage and high slope-efficiency electroabsorption modulators. Tentative plans are in place to have structures grown and devices fabricated and tested by Prof. Abdallah Ougazzaden of Georgia

Tech.

The works on THz photonic crystals may have impact in biochemical sensing.

Contributions to Human Resource Development:

Three Ph.D. students received partial support under this program. The students have variously worked on aspects of intersubband transitions in quantum wells and supporting topics related to electromagnetic propagation. The three students have received significant experience in familiarizing themselves with the relevant literature as well as have written extensive code to carry out numerical simulations of the far-infrared and optical response of quantum wells.

One PhD student, Hamza Kurt, earned his PhD under the program.

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Any Book

Any Web/Internet Site

Any Product

Contributions: To Any Resources for Research and Education

Contributions: To Any Beyond Science and Engineering

Intersubband Í'ISBÍ' transitions in semiconductor quantum wells Í'QWâ€™sÍ' span the electromagnetic spectrum from the far-infrared region1 to the near-infrared region2 and thus have important technological implementations. Due to their large oscillator strength and the ability to control the transition energy by changing the structural parameters of the QW, intersubband transitions have been successfully implemented in optoelectronic devices such as infrared Í'IRÍ' photo-detectors3 and lasers.4,5. Intersubband transitions in quantum wells have attracted tremendous attention in recent years, mainly due to the promise of applications in the mid and far-infrared regions (2--20 mum). Many of the pa.Â Many of the papers presented in Quantum Well Intersubband Transition Physics and Devices are on the basic linear intersubband transition processes, detector physics and detector application, reflecting the current state of understanding and detector applications, where highly uniform, large focal plane arrays have been demonstrated. Other areas are still in their early stages, including infrared modulation, harmonic generation and emission. Keywords. Laser Magnetic field Semiconductor Sensor Transistor infrared spectroscopy spectroscopy. Editors and affiliations. H. C. Liu.