Publications of the UCSB Center for Terahertz Science and Technology (~ July 2004)

The following publications (abstracts) document the work that has been carried out with the UCSB Free-electron Lasers at the UCSB Center for Terahertz Science and Technology. This Center is part of the Institute for Quantum Engineering, Science and Technology at UCSB. The body of work to date and described below could not have been carried out without the unique in the world UCSB FEL's or the expert staff that maintained, improved and operated the facility.

The publications are organized as follows.

Page Number

Terahertz Electro-Optics

"Strong-field terahertz optical mixing in excitons"
Su MY. Carter SG. Sherwin MS. Huntington A. Coldren LA.
Physical Review B-Condensed Matter, vol.67, no.12, 15 March 2003, pp.125307.
******
Driving a double-quantum-well excitonic intersubband resonance with a terahertz (THz) electric field of frequency omega /sub THz/ generated terahertz optical sidebands omega = omega /sub THz/+ omega /sub NIR/ on a weak near-infrared probe. At high THz intensities, the intersubband dipole energy which coupled two excitons was comparable to the THz photon energy. In this strong-field regime, the sideband intensity displayed a nonmonotonic dependence on the THz field strength. The oscillating refractive index which gives rise to the sidebands may be understood by the formation of dressed states that oscillate with the same periodicity as the driving THz field.

"Terahertz electro-optic wavelength conversion in GaAs quantum wells: Improved efficiency and room-temperature operation.",
Carter SG. Ciulin V. Sherwin MS. Hanson M. Huntington A. Coldren, LA. Gossard AC.
Applied Physics Letters, vol.84, no.6, 9 Feb. 2004, pp.840-2.
******
A 4- mu m-thick sample containing 50 GaAs/AlGaAs asymmetric coupled quantum wells was driven with a strong terahertz (THz) electric field of frequency omega /sub THz/ and probed with a near-infrared (NIR) laser of frequency omega /sub NIR/. The THz beam modulated the probe to generate sidebands at omega /sub NIR/ +n omega /sub THz/, where n is an integer. Up to 0.2% of the NIR laser power was converted into the n = + 1 sideband at 20 K, and sidebands were observed up to room temperature. The strong THz fields also induced changes in the NIR absorption of the sample.

"Terahertz optics of semiconductor nanostructures near and far from equilibrium."
Sherwin MS.
Current Opinion in Solid State & Materials Science, vol.3, 1998, pp.191-7.
******
In semiconductor nanostructures a few tens of nanometers wide, the separation between quantized states, or subbands, can be a few terahertz. In the past year, a consistent experimental picture of intersubband relaxation in wide, doped quantum wells has emerged. Terahertz radiation has also been found to dramatically alter the emission and absorption of semiconductor nanostructures near their band-edges.

"Resonant generation of terahertz optical sidebands from confined magnetoexcitons."
Kono J. Su MY. Cerne J. Sherwin MS. Allen SJ Jr. Inoshita T. Noda T. Sakaki H.
Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials & Atoms, vol.144, 1998, pp.115-22.
******
We have probed the internal structure and nonlinear response of magnetoexcitons in GaAs/AlGaAs quantum wells by resonantly driving one- and two-photon internal transitions with intense terahertz electric fields. Strong near-band-gap emission lines, or optical sidebands, appear at frequencies omega /sub NIR/+or-2n omega /sub THz/, where omega /sub NIR/ is the interband exciton-creation frequency, omega /sub THz/ is the frequency of the driving field, and n is an integer. The intensity of the sidebands exhibits pronounced enhancement when omega /sub THz/ coincides with transitions between magnetically tuned energy levels in the excitons, providing new and accurate information on the internal dynamics of excitons.

"Terahertz dynamics in confined magnetoexcitons."
Kono J. Su MY. Cerne J. Sherwin MS. Allen SJ Jr. Inoshita T. Noda T. Sakaki H.
Physica B, vol.249-251, 1998, pp.527-33.
******
We have investigated the linear and nonlinear response of confined magnetoexcitons to intense terahertz (THz) radiation. By monitoring photoluminescence from THz-driven GaAs quantum wells, we have observed for the first time internal transitions in direct excitons. The spectrum of excitations is enriched by the complexities of the valence band and is well explained by an effective-mass theory. At high THz-field strengths, the emission properties of the driven quantum wells are completely dominated by new near-band-gap features, or optical sidebands, which appear at frequencies omega /sub NIR/+or-2n omega /sub THz/, where omega /sub NIR/ is the exciton-creation

frequency, omega /sub THz/ is the driving frequency, and n is an integer. The intensity of the sidebands exhibits pronounced enhancement when omega /sub THz/ coincides with one- and two-photon exciton internal transitions.

"Excitonic dynamical Franz-Keldysh effect."
Nordstrom KB. Johnsen K. Allen SJ. Jauho A-P. Birnir B. Kono J. Noda T. Akiyama H. Sakaki H.
Physical Review Letters, vol.81, 1998, pp.457-60.
******
The dynamical Franz-Keldysh effect is exposed by exploring near-band-gap absorption in the presence of intense THz electric fields. It bridges the gap between the de Franz-Keldysh effect and multiphoton absorption and competes with the THz ac Stark effect in shifting the energy of the excitonic resonance. A theoretical model which includes the strong THz field nonperturbatively via a nonequilibrium Green functions technique is able to describe the dynamical Franz-Keldysh effect in the presence of excitonic absorption.

"Near-infrared spectroscopy of terahertz-driven semiconductor nanostructures."
Kono J. Su MY. Nordstrom KB. Ceme J. Sherwin MS. Allen SJ Jr. Noda T. Inhoshita T. Sakaki H.
Proceedings of SPIE, vol.3153, 1997, pp.96-107.
******
We have explored near-infrared (NIR)-far-infrared (FIR) two-color optical experiments in quantum-confined semiconductor systems, using NIR radiation from a tunable cw Ti:Sapphire laser and intense and coherent FIR radiation from the UCSB Free-Electron Lasers. In this paper two recent experiments are discussed, both of which provide new insight into the internal structure and dynamics of confined excitons: (1) We have observed for the first time FIR internal transitions associated with the direct exciton in GaAs/AlGaAs quantum wells. The spectrum of excitations is enriched by the complexities of the valence band and differ significantly from simple reduced-mass, hydrogenic models. We provide a critical test of detailed calculations including the valence-band mixing by Bauer and Ando (1988). (2) We have discovered resonant nonlinear optical mixing of NIR and FIR radiation, which res cally-created excitons are driven strongly by intense FIR fields. The frequencies of the sidebands are omega /sub nir/+or-2 eta omega /sub fir/, where omega /sub nir/ is the interband exciton-creation frequency, omega /sub fir/ is the frequency of the driving field, and eta is an integer. The intensity of the sidebands exhibits pronounced resonances as a function of applied magnetic field, which are well-explained in terms of virtual transitions between magnetically-tuned energy levels in the excitons.

"Resonant terahertz optical sideband generation from confined magnetoexcitons."
Kono J. Su MY. Inoshita T. Noda T. Sherwin MS. Allen SJ Jr. Sakaki H.
Physical Review Letters, vol.79, 1997, pp.1758-61.
******
We have probed the internal structure and nonlinear response of magnetoexcitons in GaAs/AlGaAs quantum wells by resonantly driving one- and two-photon internal transitions with intense terahertz electric fields. Strong near-band-gap emission lines, or optical sidebands, appear at frequencies omega /sub NIR/+or-2n omega /sub THz/, where omega /sub NIR/ is the interband exciton-creation frequency, omega /sub THz/ is the frequency of the driving field, and n is an integer. The intensity of the sidebands exhibits pronounced enhancement when omega /sub THz/ coincides with transitions between magnetically tuned energy levels in the excitons, providing new and accurate information on the internal dynamics of excitons.

"Terahertz linear and nonlinear dynamics in confined magnetoexcitons."
Kono J. Su MY. Nordstrom KB. Cerne J. Sherwin MS. Allen SJ Jr. Inoshita T. Noda T. Sakaki H. Bauer GEW. Sundaram M. Gossard AC.
Physica Status Solidi A, vol.164, 1997, pp.567-70.
******
We have probed the linear and nonlinear terahertz (THz) properties of magnetoexcitons in GaAs/AlGaAs quantum wells. By monitoring photoluminescence from the quantum wells that were simultaneously driven by THz fields, we have directly observed internal transitions of excitons. In the nonlinear, high-THz-excitation regime, we observed mixing of optical and THz radiation, which resulted in THz optical sidebands. By monitoring the sidebands, we observed one- and two-THz-photon nonlinear internal transitions in excitons. These results provide new and accurate information on the energy structure and internal dynamics of excitons.

"Observation of dynamical Franz-Keldysh effect"
Nordstrom KB. Johnsen K. Allen SJ Jr. Jauho A-P. Birnir B. Kono J. Noda T. Akiyama H. Sakaki H.
Physica Status Solidi B-Basic Research, vol.204, 1997, pp.52-4.

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We observe the linear and non-linear optical properties of a semiconductor multiple quantum well under intense terahertz irradiation to reveal a dynamical Franz-Keldysh effect. It is characterized by increased sub-gap absorption and oscillations in the absorption above the gap which vary with applied THz-field and frequency. We also observe non-linear mixing of near-bandgap light of frequency Omega /sub NIR/ with a strong Terahertz field of frequency omega /sub THz/ to produce optical sidebands at frequencies Omega /sub NIR/+or-2n omega /sub THz/. We discuss our results as a function of THz field and frequency, and compare them to our theoretical model.

“Hot excitons in quantum wells, wires, and dots.”

Cerne J. Akiyama H. Sherwin MS. Allen SJ. Someya T. Koshiba S. Sakaki H. Arakawa Y. Nagamune Y.

Proceeding of Hot Carriers in Semiconductors. Plenum Press. 1996, pp.305-8.

******

Advances in the growth of semiconductor quantum heterostructures have allowed the realization of 2-D, 1-D and 0-D quantum-confined systems. Much can be learned by investigating the equilibrium and non-equilibrium response of quantum-confined carriers to far-infrared (FIR) radiation. Investigations of photoexcited carriers are particularly interesting since neither doping nor contacts are required. We have previously observed that intense FIR radiation from UCSB's free-electron lasers (FEL) heats photoexcited carriers in quantum wells (QWs), thereby quenching excitonic photoluminescence (PL) at low lattice temperatures. In this paper, we show preliminary results on the effects of FIR radiation on photoexcited carriers in quantum wires (QWIs) and dots (QDs).

"Quenching of excitonic quantum-well photoluminescence by intense far-infrared radiation: free-carrier heating"

Cerne J. Markelz AG. Sherwin MS. Allen SJ. Sundaram M. Gossard AC. van Son PC. Bimberg D.

Physical Review B-Condensed Matter, vol.51, 1995, pp.5253-62. USA.

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Undoped GaAs/Al/sub 0.3/Ga/sub 0.7/As and and GaAs/AlAs quantum wells are simultaneously excited by weak visible light and intense far-infrared (FIR) radiation with electric fields polarized parallel to the planes of the quantum wells. The frequency of the FIR radiation ranges from 6 to 11cm/sup -1/ with intensities up to 700 kW/cm/sup 2/. Peaks in the excitonic photoluminescence (PL) are broadened and quenched by the intense FIR radiation; the PL line shapes are consistent with the FIR radiation heating the carriers without significantly heating the lattice. Despite the excitonic nature of the PL the power and frequency dependence of the carrier heating is consistent with free-carrier absorption of FIR radiation. Energy and momentum relaxation times for the free carriers are extracted from fits to a Drude model.

“Coupling of terahertz radiation with whispering-gallery-mode microdisk lasers”

Nordstrom KB. Allen SJ. Heimbuch ME. Denbaars SP. Levi AFJ.

Technical Digest Series Conference Edition (Cat. No.94CH3462-9). Opt. Soc. America. 1994, pp.152-3.

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Summary form only given. Whispering-gallery-mode microdisk lasers offer a unique opportunity for studying high-frequency mode-locking by coupling their cavity modes and collective electron modes by using externally-applied radiation. We have successfully fabricated microdisk lasers, driven them with terahertz radiation from the UCSB FEL, and observed spectral redistribution of the laser intensity. We discuss these results in terms of the collective carrier dynamics, the laser mode structure, and their interaction. Our microdisks were fabricated on OMCVD-grown InP/InGaAsP material. Four unstrained InGaAs quantum wells with InGaAsP barriers and InGaAsP end layers were grown on an InP substrate. The disks were patterned lithographically and were defined with a reactive-ion etch.

“Photoluminescence as a probe of the interaction of intense far-infrared radiation with semiconductor quantum structures”

van Son PC. Cerne J. Sherwin MS. Allen SJ Jr. Sundaram M. Tan I-H. Bimberg D.

Nuclear Instruments & Methods in Physics Research Section A-Accelerators Spectrometers Detectors & Associated Equipment, vol.341, 1994, pp.174-7.

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At the UCSB free-electron laser we have realized a set-up to detect the photoluminescence from semiconductor quantum structures while they are irradiated with intense far-infrared radiation. The effect of the radiation on both quantum wells and quantum-well wires has been identified with non-resonant carrier heating. The confined carriers in these structures have energy-level spacings in the far-infrared region of the spectrum. The tunability of the free-electron laser therefore allows the study of resonant effects as well.

“Strong-field terahertz optical mixing in excitons”
Su MY. Carter SG. Sherwin MS. Huntington A. Coldren LA.
Physical Review B-Condensed Matter, vol.67, 2003, pp.125307-1-5.
******
Driving a double-quantum-well excitonic intersubband resonance with a terahertz (THz) electric field of frequency omega /sub THz/ generated terahertz optical sidebands omega = omega /sub THz/+ omega /sub NIR/ on a weak near-infrared probe. At high THz intensities, the intersubband dipole energy which coupled two excitons was comparable to the THz photon energy. In this strong-field regime, the sideband intensity displayed a nonmonotonic dependence on the THz field strength. The oscillating refractive index which gives rise to the sidebands may be understood by the formation of dressed states that oscillate with the same periodicity as the driving THz field.

“Photothermal transitions of magnetoexcitons in GaAs/Al/sub x/Ga/sub 1-x/As quantum wells”
Cerne J. Kono J. Su M. Sherwin MS
Physical Review B-Condensed Matter, vol.66, 2002, pp.205301-1-6.
******
By monitoring changes in excitonic photoluminescence (PL) that are induced by terahertz (THz) radiation, we observe resonant THz absorption by magnetoexcitons in GaAs/Al/sub x/Ga/sub 1-x/As quantum wells. Changes in the PL spectrum are explored as a function of temperature and magnetic field, providing insight into the mechanisms which allow THz absorption to modulate PL. The strongest PL-quenching occurs at the heavy hole 1s to 2p/sup +/ resonance where heavy hole excitons are photothermally converted into light hole excitons.

“Nonperturbative terahertz nonlinear optics of excitons”
Su MY. Carter S. Sherwin MS. Huntington A. Coldren LA. Kadow C. Gossard A
Summaries of papers presented at the Quantum Electronics and Laser Science Conference. Conference Edition (IEEE Cat. No.02CH37338). Opt. Soc. America. Part vol.1, 2002, pp.61-2 vol.1.
******
Summary form only given. We performed experiments where a near-infrared (NIR) probe laser beam is mixed with an intense terahertz (THz) pump beam in a gated, asymmetric double quantum-well The THz field couples to an excitonic intersubband excitation while the NIR field couples to an excitonic interband excitation.

“Voltage-controlled wavelength conversion by terahertz electro-optic modulation in double quantum wells”
Su MY. Carter SG. Sherwin MS. Huntington A. Coldren LA.
Applied Physics Letters, vol.81, 2002, pp.1564-6.
******
An undoped double quantum well (DQW) was driven with a terahertz (THz) electric field of frequency omega /sub THz/ polarized in the growth direction, while simultaneously illuminated with a near-infrared (NIR) laser at frequency omega /sub NIR/. The intensity of NIR upconverted sidebands omega /sub sideband/= omega /sub NIR/+ omega /sub THz/ was maximized when a dc voltage applied in the growth direction tuned the excitonic states into resonance with both the THz and NIR fields. There was no detectable upconversion far from resonance. The results demonstrate the possibility of using gated DQW devices for all-optical wavelength shifting between optical communication channels separated by up to a few THz.

“First-order coherent THz optical sideband generation from asymmetric QW intersubband transitions”
Phillips C. Su MY. Ko J. Coldren L. Sherwin MS
Physica E, vol.7, 2000, pp.187-90.
******
We have generated terahertz (THz) optical sidebands on a near-infrared probe beam by driving an excitonic intersubband resonance with THz electric fields. We use THz radiation polarized along the non-centro-symmetric axis of a quantum well system to generate a comb of sidebands omega /sub sideband/= omega /sub NIR/+n omega /sub THz/. In exploring the rich polarization of the process's power, and NIR frequency dependences we encounter both an efficient perturbative regime modeled by a X/sup (2)/ non-linear susceptibility, and a non-perturbative regime which has not been previously explored in driven quantum systems.

“Odd terahertz optical sidebands from asymmetric excitonic intersubband excitation”
Su MY. Phillips C. Ko J. Coldren L. Sherwin MS
Physica B, vol.272, 1999, pp.438-41.
******

We have generated terahertz (THz) optical sidebands on a near-infrared probe beam by driving an excitonic intersubband resonance with THz electric fields. We use THz radiation polarized along the non-centrosymmetric axis of a quantum well system to generate a comb of sidebands omega /sub sideband/= omega /sub NIR/+n omega /sub THz/. In exploring the process's rich polarization, power, and NIR frequency dependences we encounter both an efficient perturbative regime modeled by a chi /sup (2)/ non-linear susceptibility, and a non-perturbative regime which has not been previously explored in driven quantum systems.

"Coherent terahertz mixing spectroscopy of asymmetric quantum well intersubband transitions"
Su MY. Phillips C. Kadow C. Ko J. Coldren LA. Gossard AC. Sherwin MS.
Proceedings of Spie, vol.3617, 1999, pp.106-11.
******
Since terahertz electric fields can couple strongly to quantum well intersubband transitions we expect interband optical properties of a semiconductor heterostructure to change resonantly under a THz driving field. By driving the excitonic intersubband resonance of an asymmetric quantum well with intense THz electric fields from a free electron laser, we modulate the transmission of a near-IR (NIR) laser beam at terahertz frequencies. This process manifests itself as the emission of optical sidebands on the NIR probe. In previous THz electro-optical studies in semiconductors, only even sidebands of frequency omega /sub sideband/= omega /sub NIR/+2n omega /sub THz/ had been observed. By breaking inversion symmetry we are able to generate a comb of even and odd sidebands. The sidebands obey both THz and near-IR polarization selection rules and are enhanced when the NIR energy is res nds of all orders is important for the future application of THz EO effects in nonlinear spectroscopy and in ultrafast optical phase and amplitude modulation.

"Generation of first-order terahertz optical sidebands in asymmetric coupled quantum wells."
Phillips C. Su MY. Sherwin MS. Ko J. Coldren L.
Applied Physics Letters, vol.75, 1999, pp.2728-30.
******
We have generated first-order tetrahertz (THz) optical sidebands on a near-infrared (NIR) probe beam by driving an excitonic intersubband resonance with THz electric fields. We use THz radiation polarized along the noncentrosymmetric axis of a quantum well system to generate a comb of sidebands omega /sub sideband/= omega /sub NIR/+n omega /sub THz/. The n=process offers an efficient means of modulating a NIR carrier beam at THz frequencies and yields new spectroscopic information on excitonic intersubband transitions.

"Resonant generation of terahertz optical sidebands from confined magnetoexcitons".
Kono J. Su MY. Cerne J. Sherwin MS. Allen SJ Jr. Inoshita T. Noda T. Sakaki H.
Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials & Atoms, vol.144, 1998, pp.115-22.
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We have probed the internal structure and nonlinear response of magnetoexcitons in GaAs/AlGaAs quantum wells by resonantly driving one- and two-photon internal transitions with intense terahertz electric fields. Strong near-band-gap emission lines, or optical sidebands, appear at frequencies omega /sub NIR/+or-2n omega /sub THz/, where omega /sub NIR/ is the interband exciton-creation frequency, omega /sub THz/ is the frequency of the driving field, and n is an integer. The intensity of the sidebands exhibits pronounced enhancement when omega /sub THz/ coincides with transitions between magnetically tuned energy levels in the excitons, providing new and accurate information on the internal dynamics of excitons.

"Terahertz dynamics in confined magnetoexcitons"
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We have investigated the linear and nonlinear response of confined magnetoexcitons to intense terahertz (THz) radiation. By monitoring photoluminescence from THz-driven GaAs quantum wells, we have observed for the first time internal transitions in direct excitons. The spectrum of excitations is enriched by the complexities of the valence band and is well explained by an effective-mass theory. At high THz-field strengths, the emission properties of the driven quantum wells are completely dominated by new near-band-gap features, or optical sidebands, which appear at frequencies omega /sub NIR/+or-2n omega /sub THz/, where omega /sub NIR/ is the exciton-creation frequency, omega /sub THz/ is the driving frequency, and n is an integer. The intensity of the sidebands exhibits pronounced enhancement when omega /sub THz/ coincides with one- and two-photon exciton internal transitions.

“Near-infrared spectroscopy of terahertz-driven semiconductor nanostructures”
Kono J. Su MY. Nordstrom KB. Ceme J. Sherwin MS. Allen SJ Jr. Noda T. Inhoshita T. Sakaki H.
Proceedings of the SPIE, vol.3153, 1997, pp.96-107.
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We have explored near-infrared (NIR)-far-infrared (FIR) two-color optical experiments in quantum-confined semiconductor systems, using NIR radiation from a tunable cw Ti:Sapphire laser and intense and coherent FIR radiation from the UCSB Free-Electron Lasers. In this paper two recent experiments are discussed, both of which provide new insight into the internal structure and dynamics of confined excitons: (1) We have observed for the first time FIR internal transitions associated with the direct exciton in GaAs/AlGaAs quantum wells. The spectrum of excitations is enriched by the complexities of the valence band and differ significantly from simple reduced-mass, hydrogenic models. We provide a critical test of detailed calculations including the valence-band mixing by Bauer and Ando (1988). (2) We have discovered resonant nonlinear optical mixing of NIR and FIR radiation, which res cally-created excitons are driven strongly by intense FIR fields. The frequencies of the sidebands are omega /sub nir/+or-2 eta omega /sub fir/, where omega /sub nir/ is the interband exciton-creation frequency, omega /sub fir/ is the frequency of the driving field, and eta is an integer. The intensity of the sidebands exhibits pronounced resonances as a function of applied magnetic field, which are well-explained in terms of virtual transitions between magnetically-tuned energy levels in the excitons.

“Resonant terahertz optical sideband generation from confined magnetoexcitons”
Kono J. Su MY. Inoshita T. Noda T. Sherwin MS. Allen SJ Jr. Sakaki H.
Physical Review Letters, vol.79, 1997, pp.1758-61.
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We have probed the internal structure and nonlinear response of magnetoexcitons in GaAs/AlGaAs quantum wells by resonantly driving one- and two-photon internal transitions with intense terahertz electric fields. Strong near-band-gap emission lines, or optical sidebands, appear at frequencies omega /sub NIR/+or-2n omega /sub THz/, where omega /sub NIR/ is the interband exciton-creation frequency, omega /sub THz/ is the frequency of the driving field, and n is an integer. The intensity of the sidebands exhibits pronounced enhancement when omega /sub THz/ coincides with transitions between magnetically tuned energy levels in the excitons, providing new and accurate information on the internal dynamics of excitons.

“Near-infrared sideband generation induced by intense far-infrared radiation in GaAs quantum wells”
Cerne J. Kono J. Inoshita T. Sherwin M. Sundaram M. Gossard AC.
Applied Physics Letters, vol.70, no.26, 30 June 1997, pp.3543-5.
Publisher: AIP, USA.
******
GaAs quantum wells are simultaneously illuminated with near-infrared (NIR) radiation at frequency omega /sub nir/ and intense far-infrared (FIR) radiation from a free-electron laser at omega /sub fir/. Magnetic fields up to 9 T are applied. Strong and narrow sidebands are observed at omega /sub sideband/= omega /sub nir/+or-2 omega /sub fir/. The intensity of the sidebands is enhanced when either omega /sub sideband/ or omega /sub nir/ is near the onset of NIR absorption in the quantum well, or when omega /sub fir/, is near the free-electron cyclotron frequency. We attribute these sidebands to four-wave mixing of NIR and FIR photons whose energies differ by more than a factor of 100.

“Terahertz linear and nonlinear dynamics in confined magnetoexcitons”
Kono J. Su MY. Nordstrom KB. Cerne J. Sherwin MS. Allen SJ Jr. Inoshita T. Noda T. Sakaki H. Bauer GEW. Sundaram M. Gossard AC.
Physica Status Solidi A, vol.164, 1997, pp.567-70.
******
We have probed the linear and nonlinear terahertz (THz) properties of magnetoexcitons in GaAs/AlGaAs quantum wells. By monitoring photoluminescence from the quantum wells that were simultaneously driven by THz fields, we have directly observed internal transitions of excitons. In the nonlinear, high-THz-excitation regime, we observed mixing of optical and THz radiation, which resulted in THz optical sidebands. By monitoring the sidebands, we observed one- and two-THz-photon nonlinear internal transitions in excitons. These results provide new and accurate information on the energy structure and internal dynamics of excitons.

“Optically-detected far-infrared exciton resonance in GaAs/AlGaAs quantum wells”
Cerne J. Kono J. Sherwin MS. Sundaram M. Gossard AC. Bauer GEW.

Proceedings of 23rd International Conference on the Physics of Semiconductors. World Scientific. vol.3, 1996, pp.1923-6.
******
We report the first observation of internal transitions of excitons in GaAs/AlGaAs quantum wells. The resonant far-infrared (FIR) absorption was magnetically tuned and optically detected, using excitonic photoluminescence. Several excitonic transitions and free-electron cyclotron resonance were observed. We assign the dominant excitonic resonance to the 1s to 2p/sup +/ heavy-hole exciton transition, whose energy vs. magnetic field was in excellent agreement with detailed calculations for magnetoexcitons by Bauer and Ando.

“Mixing of near-infrared radiation with intense far-infrared radiation in GaAs/AlGaAs quantum wells.”
Kono J. Cerne J. Inoshita T. Sherwin MS. Sundaram M. Gossard AC. Proceedings of the 23rd International Conference on the Physics of Semiconductors. World Scientific. Part vol.3, 1996, pp.1911-14.
******
We have observed nonlinear-optical mixing of near-infrared (NIR) radiation with intense far-infrared (FIR) radiation in GaAs/AlGaAs quantum wells, which produced strong and narrow NIR sidebands that are separated from the fundamental NIR probe energy by two FIR photon energies. This effect was enhanced when either the sideband or the NIR pump energy was at the band edge of the quantum well, or when the FIR frequency was near the electron cyclotron frequency. The results are discussed in terms of a chi /sup (3)/ process involving a NIR photon and two FIR photons.

“Hot excitons in quantum wells, wires, and dots”
Cerne J. Akiyama H. Sherwin MS. Allen SJ. Someya T. Koshiba S. Sakaki H. Arakawa Y. Nagamune Y.
Proceeding of Hot Carriers in Semiconductors. Plenum Press. 1996, pp.305-8. New York
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Advances in the growth of semiconductor quantum heterostructures have allowed the realization of 2-D, 1-D and 0-D quantum-confined systems. Much can be learned by investigating the equilibrium and non-equilibrium response of quantum-confined carriers to far-infrared (FIR) radiation. Investigations of photoexcited carriers are particularly interesting since neither doping nor contacts are required. We have previously observed that intense FIR radiation from UCSB's free-electron lasers (FEL) heats photoexcited carriers in quantum wells (QWs), thereby quenching excitonic photoluminescence (PL) at low lattice temperatures. In this paper, we show preliminary results on the effects of FIR radiation on photoexcited carriers in quantum wires (QWIs) and dots (QDs).

“Terahertz dynamics of excitons in GaAs/AlGaAs quantum wells”
Cerne J. Kono J. Sherwin MS. Sundaram M. Gossard AC. Bauer GEW.
Physical Review Letters, vol.77, 1996, pp.1131-4.
******
By monitoring changes in excitonic photoluminescence that are induced by far-infrared (FIR) radiation, we observed resonant FIR absorption by magnetoexcitons in GaAs/AlGaAs quantum wells. The dominant resonance is assigned to the 1s to 2p/sup +/ transition of the heavy-hole exciton, and agrees well with theory. At low FIR and interband excitation intensities, the is 1s to 2p/sup +/ absorption feature is very narrow and broadens as either of these intensities is increased. The is 1s to 2p/sup +/ absorption feature persists even when the FIR electric field is comparable to the electric field which binds the exciton.

“Quenching of excitonic quantum-well photoluminescence by intense far-infrared radiation: free-carrier heating”
Cerne J. Markelz AG. Sherwin MS. Allen SJ. Sundaram M. Gossard AC. van Son PC. Bimberg D.
Physical Review B-Condensed Matter, vol.51, no.8, 15 Feb. 1995,
pp.5253-62. USA.
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Undoped GaAs/Al/sub 0.3/Ga/sub 0.7/As and and GaAs/AlAs quantum wells are simultaneously excited by weak visible light and intense far-infrared (FIR) radiation with electric fields polarized parallel to the planes of the quantum wells. The frequency of the FIR radiation ranges from 6 to 11cm/sup -1/ with intensities up to 700 kW/cm/sup 2/. Peaks in the excitonic photoluminescence (PL) are broadened and quenched by the intense FIR radiation; the PL line shapes are consistent with the FIR radiation heating the carriers without significantly heating the lattice. Despite the excitonic nature of the PL the power and frequency dependence of the carrier heating is consistent with free-carrier absorption of FIR radiation. Energy and momentum relaxation times for the free carriers are extracted from fits to a Drude model.

“Photoluminescence as a probe of the interaction of intense far-infrared radiation with semiconductor quantum structures”
van Son PC. Cerne J. Sherwin MS. Allen SJ Jr. Sundaram M. Tan I-H. Bimberg D.
Nuclear Instruments & Methods in Physics Research Section A-Accelerators
Spectrometers Detectors & Associated Equipment, vol.341, 1994, pp.174-7.
******
At the UCSB free-electron laser we have realized a set-up to detect the photoluminescence from semiconductor quantum structures while they are irradiated with intense far-infrared radiation. The effect of the radiation on both quantum wells and quantum-well wires has been identified with non-resonant carrier heating. The confined carriers in these structures have energy-level spacings in the far-infrared region of the spectrum. The tunability of the free-electron laser therefore allows the study of resonant effects as well.

“Photoluminescence from Al/sub x/Ga/sub 1-x/As/GaAs quantum wells quenched by intense far-infrared radiation”
Quinlan SM. Nikroo A. Sherwin MS. Sundaram M. Gossard AC.
Physical Review B-Condensed Matter, vol.45, 1992, pp.9428-31.
******
The authors present an experimental study of the effects of intense far-infrared (FIR) radiation on the excitonic photoluminescence (PL) from Al/sub x/Ga/sub 1-x/As/GaAs quantum wells. The FIR electric field was polarized parallel to the plane of undoped, 100-AA-wide Al/sub 0.3/Ga/sub 0.7/As/GaAs wells. Electron-hole pairs, created by relatively weak visible pulses, were excited by FIR pulses with intensities of up to 70 kW/cm/sup 2/ at frequencies of 29.5 and 43.3 cm/sup -1/ (3.7 and 5.4 meV). Both quenching and broadening of free-exciton PL peaks were observed for RMS FIR field strengths above a threshold of order 100 V/cm.

Terahertz Coherent Quantum Control

“Coherent manipulation of semiconductor quantum bits with terahertz radiation”
Cole BE. Williams JB. King BT. Sherwin MS. Stanley CR.
Nature, vol.410, 2001, pp.60-3.
******
Quantum bits (qubits) are the fundamental building blocks of quantum information processors, such as quantum computers. A qubit comprises a pair of well characterized quantum states that can in principle be manipulated quickly compared to the time it takes them to decohere by coupling to their environment. Much remains to be understood about the manipulation and decoherence of semiconductor qubits. Here we show that hydrogen-atom-like motional states of electrons bound to donor impurities in currently available semiconductors can serve as model qubits. We use intense pulses of terahertz radiation to induce coherent, damped Rabi oscillations in the population of two low-lying states of donor impurities in GaAs. Our observations demonstrate that a quantum-confined extrinsic electron in a semiconductor can be coherently manipulated like an atomic electron, even while sharing space wi ul for measuring intrinsic decoherence processes, and for testing both simple and complex manipulations of semiconductor qubits.

“Quantum computation with quantum dots and terahertz cavity quantum electrodynamics”
Sherwin MS. Imamoglu A. Montroy T.
Physical Review A, vol.60, 1999, pp.3508-14.
******
A quantum computer is proposed in which information is stored in the two lowest electronic states of doped quantum dots (QD's). Many QD's are located in a microcavity. A pair of gates controls the energy levels in each QD. A controlled-NOT (C-NOT) operation involving any pair of QD's can be effected by a sequence of gate-voltage pulses which tune the QD energy levels into resonance with frequencies of the cavity or a laser. The duration of a C-NOT operation is estimated to be much shorter than the time for an electron to decohere by emitting an acoustic phonon.

“Coherent transfer and electron teleportation in semiconductor double quantum well.”
Rufenacht M. Tsujino S. Allen SJ. Schoenfeld W. Petroff P.
Physica Status Solidi B-Basic Research, vol.221, no.1, 1 Sept. 2000, pp.407-11.

******
When three or more levels are simultaneously coupled by light in a charge transfer double quantum well (QW), it is possible to transfer electrons coherently between the QWs. Using two light pulses of different wavelengths, the transient occupation of the space between the two QWs can be made arbitrarily small: electron teleportation. We discuss this phenomenon within a single electron model, estimate the effect of decoherence, and compare our results with experiments.

"Quantum control of electron transfer."
Tsujino S. Rufenacht M. Miranda P. Allen SJ. Tamborenea P. Schoenfeld W. Herold G. Lupke G. Lundstrom T. Petroff P. Metiu H. Moses D.,
Physica Status Solidi B-Basic Research, vol.221, no.1, 1 Sept. 2000, pp.391-6.
******
We explore electron transfer in double quantum well structures induced by femtosecond mid-infrared intersubband excitation. Spatial transfer of electrons from one quantum well to its hole filled neighbor is detected by recombination luminescence. The process results in upconversion of the mid-infrared exciting light to near-infrared luminescence. Two mid-infrared pulses with variable time delay allow us to display the field and intensity autocorrelation function for the upconverted signal and measure the electron transfer dynamics. Electron transfer between the GaAs quantum wells separated by 300 nm can be saturated and the intensity autocorrelation function exhibits a slow 18 ps recovery. Transfer between wells separated by only 25 nm is coherently controlled by the phase of the two collinear infrared pulses.

Superconductivity

"Midinfrared studies of the contact region at superconductor-semiconductor interfaces."
Eckhause TA. Tsujino S. Lehnert KW. Gwinn EG. Allen SJ. Thomas M. Kroemer H.
Applied Physics Letters, vol.76, (2000), pp.215-17.
******
InAs quantum wells (QWs) have been used as weak links in many recent studies of novel superconductor-normal metal-superconductor junctions. The degree of coupling between the superconducting electrodes depends sensitively on both the superconductor/InAs interface and the QW material in the weak link, factors that are difficult to separate in dc transport studies. Here we used midinfrared spectroscopy to investigate the superconductor/semiconductor contact region. The remnant intersubband absorption we observe in Nb-clad InAs shows that the superconductor/InAs interface produced some confinement of electrons in the InAs. This confinement is, however, consistent with phase coherent transport in the InAs. We find no evidence for charge transfer from the superconductor to the InAs on cooling below the critical temperature of Nb.

"Nonequilibrium superconductivity in mesoscopic Nb/InAs/Nb junctions."
Lehnert KW. Harris JGE. Allen SJ. Argaman N.
Superlattices & Microstructures, vol.25, no.5-6, 1999.
******
We review experiments on the response of Nb/InAs/Nb SNS junctions to high frequency irradiation. Both single junctions and multi-junction arrays show an anomalous half-integer Shapiro step, which persists to high temperatures in the absence of a critical current. The temperature and bias dependence of this effect demonstrate that it is caused by nonequilibrium AC supercurrents flowing at twice the usual frequency. Conductance enhancement near zero bias is also observed and attributed to nonequilibrium dynamics. A model based on time-dependent Andreev bound states, with parameters extracted from this enhanced conductance, successfully accounts for this half-integer Shapiro step.

"Nonequilibrium supercurrents in mesoscopic Nb-InAs-Nb junctions."
Lehnert KW. Argaman N. Blank H-R. Wong KC. Allen SJ. Hu EL. Kroemer H.
Microelectronic Engineering, vol.47,pp.377-9, 1998.
******
Microwave irradiation of Nb-InAs-Nb single-junctions demonstrates that the half-integer Shapiro step is caused by ac nonequilibrium supercurrent. In addition, nonequilibrium dc supercurrents are observed as a conductance

enhancement around zero bias. Both effects persist to temperatures well above the disappearance of the equilibrium critical current and integer Shapiro step.

"Nonequilibrium AC Josephson effect in mesoscopic Nb-InAs-Nb junctions."
Lehnert KW. Argaman N. Blank H-R. Wong KC. Allen SJ. Hu EL. Kroemer H.
Physical Review Letters, vol.82, no.6, 8 Feb. 1999, pp.1265-8.
******
Microwave irradiation of Nb-InAs-Nb junctions reveals frequency-doubled Josephson currents which persist to high temperatures, in the absence of a critical current. A nonequilibrium dynamical model, based on time-dependent Andreev bound states, successfully accounts for the resulting half-integer Shapiro step and an enhancement in the conductance near zero bias.

"Superconductivity and the Josephson effect in a periodic array of Nb-InAs-Nb junctions.
Drexler H. Harris JGE. Yuh EL. Wong KC. Allen SJ. Gwinn EG. Kroemer H. Hu EL.
Surface Science, vol.361-362, 20 July 1996, pp.306-10.
******
We have applied high-frequency radiation to a one-dimensional array of superconducting-normal-superconducting junctions, comprised of Nb-2DInAs-Nb, and observed Shapiro steps in the I-V curve which are dominated by a step at V=hv/4e, half the voltage of the usual AC Josephson effect. This result is discussed in view of a coupling between the Nb stripes that differs from the usual j/sub c/ sin Phi form. The zero-bias resistance of the sample is finite and increases exponentially with temperature. The Shapiro steps, however, persist up to the Nb transition temperature. These results imply that the finite resistance of the sample originates from excitations in the superconducting state.

"Intersubband absorption in Nb-clad InAs quantum wells"
Eckhause TA. Tsujino S. Gwinn EG. Thomas M. Kroemer H.
Physica E, vol.6, 2000, pp.856-9.
******
We use mid-infrared (MIR) spectroscopy to investigate the contact region at the Nb/InAs superconductor/semiconductor interface. We observe a remnant of the intersubband (ISB) resonance in Nb-clad InAs quantum wells, both in samples where we have grown Nb directly on InAs in situ, and samples where we have etch exposed the InAs surface before depositing the Nb. The presence of this remnant ISB indicates partial confinement of the electrons to the InAs. The similar resonance widths in the MBE grown Nb/InAs sample and the samples with Nb on etched InAs suggest that coupling of electron states in the InAs to those in Nb, rather than etch-induced damage, produces most of the resonance broadening.

"Far-infrared studies of induced superconductivity in quantum wells"
Yuh EL. Harris JGE. Eckhause T. Wong KC. Gwinn EG. Kroemer H. Allen S.
Surface Science, vol.361-362, 20 July 1996, pp.315-19.
******
Recent work on periodic SNS microstructures, in which a superconductor grating contacts an underlying InAs quantum well, has demonstrated that supercurrents can flow across the strips of quasi-two-dimensional electron gas between the superconductor grating lines. Here we show that the loss of DC resistance is accompanied by the emergence of striking features in the samples excitation spectra, for energies below ~2 Delta . Although such series weak-link structures may display a Josephson plasmon resonance, the changes in the samples far-infrared transmission in an applied H field appear to be inconsistent with the behavior expected for this mode. The transmission spectra also differ from the form expected for an energy gap in the quantum well strips between adjacent superconductor lines.

"Superconductivity and the Josephson effect in a periodic array of Nb-InAs-Nb junctions"
Drexler H. Harris JGE. Yuh EL. Wong KC. Allen SJ. Gwinn EG. Kroemer H. Hu EL.
Surface Science, vol.361-362, 1996, pp.306-10.
******
We have applied high-frequency radiation to a one-dimensional array of superconducting-normal-superconducting junctions, comprised of Nb-2DInAs-Nb, and observed Shapiro steps in the I-V curve which are dominated by a step at V=hv/4e, half the voltage of the usual AC Josephson effect. This result is discussed in view of a coupling between the Nb stripes that differs from the usual j/sub c/ sin Phi form. The zero-bias resistance of the sample is finite and increases exponentially with temperature. The Shapiro steps, however, persist up to the Nb transition temperature. These results imply that the finite resistance of the sample originates from excitations in the superconducting state.

Terahertz Photon Assisted Transport

“Observation of Shapiro steps and direct evidence of Bloch oscillations in semiconductor superlattices.”
Unterrainer K. Keay BJ. Wanke MC. Allen SJ. Leonard D. Medeiros-Ribeiro G. Bhattacharya U. Rodwell MJW.
Proceedings of the 23rd Intern. Symp. on Compound Semiconductors. IOP Publishing. 1997,
pp.729-34. Bristol, UK.
******
We have observed resonant changes in the current-voltage characteristics of miniband semiconductor superlattices when the Bloch frequency is resonant with a terahertz field and its harmonics: the inverse Bloch oscillator effect. The resonant feature consists of a peak in the current, which grows with increasing laser intensity accompanied by a decrease of the current at the low bias side. When the intensity is increased further the first peak starts to decrease and a second peak at about twice the voltage of the first peak is observed due to a two-photon resonance. At the highest intensities we observe up to a four-photon resonance. This is an analogy of Shapiro steps in a S-I-S junction subject to the AC Josephson effect. The increase of the current is caused by stimulated emission of photons and from the value of the induced current we can estimate the THz gain of the superlattice.

“Terahertz, photon-assisted transport in semiconductor quantum structures.”
Allen SJ.
Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials & Atoms, vol.144, 1998, pp.130-4.
******
We review experiments carried out at UC Santa Barbara, with terahertz free electron lasers, that have graphically exposed several aspects of photon assisted transport in semiconductor quantum structures. Heretofore this phenomenon was restricted to superconducting electronics at low temperatures. In semiconductor quantum structures, photon assisted transport is not restricted to low temperatures but rather high frequencies and has many attributes that make it potentially important for future terahertz electronics. (9

“Resonantly enhanced photon-assisted tunneling in a multiple-quantum-well superlattice.”
Vieira GS. Allen SJ. Guimaraes PSS. Campman KL. Gossard AC.
Physical Review B-Condensed Matter, vol.58, 1998, pp.7136-40.
Photon-assisted tunneling in a multiple-quantum-well superlattice is enhanced as the photon energy becomes resonant with the first intersubband transition. At resonance the process is characterized by tunneling from real states occupied by photoexcitation. Qualitative differences emerge between photon-assisted tunneling controlled by virtual states, under off-resonance conditions, and photon-assisted tunneling from real states, occupied by photoexcitation when on resonance.

“Sequential tunneling in doped superlattices: fingerprints of impurity bands and photon-assisted tunneling”
Wacker A. Jauho A-P. Zeuner S. Allen SJ.
Physical Review B-Condensed Matter, vol.56, 1997, pp.13268-78.
******
We report a combined theoretical and experimental study of electrical transport in weakly coupled doped superlattices. Our calculations exhibit negative differential conductivity at sufficiently high electric fields for all dopings. In low-doped samples the presence of impurity bands modifies the current-voltage characteristics substantially, and we find two different current peaks whose relative height changes with the electron temperature. These findings can explain the observation of different peaks in the current-voltage characteristics with and without external THz irradiation in low-doped samples. From our microscopic transport model we obtain quantitative agreement with the experimental current-voltage characteristics without using any fitting parameters. Both our experimental data and our theory show that absolute negative conductance persists over a wide range of frequencies.

“THz response of GaAs/AlGaAs superlattices: from classical to quantum dynamics.”
Zeuner S. Keay BJ. Allen SJ. Maranowski KD. Gossard AC. Bhattacharya U. Rodwell MJW.
Superlattices & Microstructures, vol.22, 1997, pp.149-54.
******
We have investigated the THz response of a series of GaAs/Al/sub x/Ga/sub 1-x/As superlattices with a variety of minibands widths. The samples range from the sequential resonant tunneling limit with a very narrow miniband to superlattices show a transition from classical rectification at frequencies below 600 GHz to quantum response above 1 THz. In the quantum regime, the I-V show distinct peaks due to absorption and stimulated emission of up to seven

THz-photons. At high a.c. field strengths (several kV cm/sup -1/) the photon-assisted channels dominate the transport, leading to dynamic localization, absolute negative conductance, and gain just below the Stark splitting of the quantum well ground-states. The transition from classical to quantum behavior takes place at a frequency where h omega ~ Gamma , where Gamma approximately=2 meV is the ground-state level width in a single quantum well."

"Transition from classical to quantum dynamics in superlattices in intense THz electrical fields."
Zeuner S. Keay BJ. Allen SJ. Maranowski KD. Gossard AC. Bhattacharya U. Rodwell MJW.
Proceedings of the International Conference on Quantum Devices and
Circuits. World Scientific. 1997, pp.124-9.
******
We have investigated the THz-response of a series of GaAs/Al/sub x/Ga/sub 1-x/As superlattices ranging from the sequential tunneling limit to superlattices with a miniband width of 10 meV. In the sequential resonant tunneling case we observe a transition from classical rectification at frequencies below 600 GHz to quantum response above 1 THz. In the quantum regime, the current-voltage characteristics show distinct peaks due to absorption and stimulated emission of up to three THz-photons. At high THz field strengths (~10 kV/cm) the photon-assisted channels dominate the transport, leading to dynamic localization, absolute negative conductance, and gain just below the Stark splitting of the quantum well ground-states. In the classical regime the irradiated I-Vs show no frequency dependent features. .

"Photon-assisted electric field domains and multiphoton-assisted tunneling in antenna coupled semiconductor superlattices."
Keay BJ. Allen SJ Jr. Galan J. Campman KL. Gossard AC. Bhattacharya U. Rodwell MJW.
Proceedings of Hot Carriers in Semiconductors. Plenum Press. 1996, pp.139-42.
******
We show that the photon-assisted tunneling (PAT) channels can also support high and low field domains if the terahertz field is strong enough. By using bow tie antennas we have improved the coupling of terahertz radiation into semiconductor superlattices, thereby enabling us to explore PAT induced inhomogeneities as well as multiphoton assisted tunneling and the terahertz electric field dependence of the PAT channels. An extension of the model of Bonilla et al. (Phys. Rev. B vol.50, p.8644, 1994) is put forward that can account in a quantitative way for the detailed I-V characteristics of these systems in strong high frequency fields, including both PAT channels and their effect on the electric field domain distribution.

"Strong terahertz-photocurrent resonances in miniband superlattices at the Bloch frequency."
Unterrainer K. Keay BJ. Wanke MC. Allen SJ. Leonard D. Medeiros-Ribeiro G. Bhattacharya U. Rodwell MJW.
Proceedings of Hot Carriers in Semiconductors. Plenum Press. 1996, pp.135-8.
******
We have observed resonant changes in the current-voltage characteristics of miniband semiconductor superlattices when the Bloch frequency is resonant with a terahertz field and its harmonics. This corresponds to absorption and gain of THz radiation in the Wannier Stark ladder of the superlattice. The resonant feature consists of a peak in the current which grows with increasing laser intensity accompanied by a decrease of the current at the low bias side. When the intensity is increased further the first peak starts to decrease and a second peak at about twice the voltage of the first peak is observed due to a two-photon resonance. At the highest intensities we observe up to a four-photon resonance.

"Photon assisted transport through semiconductor quantum structures in intense terahertz electric fields."
Allen SJ. Bhattacharya U. Campman K. Drexler H. Gossard A. Keay BJ. Maranowski K. Medeiros-Ribeiro G. Rodwell M. Scott JS. Unterrainer C. Wanke M. Zeuner S.
Physica B, vol.227, no.1-4, Sept. 1996, pp.367-72.
******
Quantum transport in resonant tunneling diodes, sequential resonant tunneling superlattices and miniband superlattices in the presence of intense terahertz electric fields is marked by new channels opened by the absorption or emission of one or more terahertz photons. In triple barrier resonant tunneling diodes, new transport channels supported by the absorption or stimulated emission of up to three terahertz photons are observed. In sequential resonant tunneling superlattices, dynamic localization is accompanied by absolute negative resistance. Transport in miniband superlattices, controlled by coherent tunneling through several barriers and quantum wells, reveals multi-photon resonances with Bloch oscillation. Photon-assisted transport in these semiconductor quantum structures bears a strong analogy to quasi-particle tunneling and the AC Josephson effect in superconducting junct nts are made possible by the UCSB free-electron lasers that deliver kilowatts of tunable radiation from 120 GHz to 4.8 THz. (19

“Virtual states, dynamic localization, absolute negative conductance and stimulated multiphoton emission in semiconductor superlattices.”
Keay BJ. Aversa C. Zeuner S. Allen SJ Jr. Campman KL. Maranowski KD. Gossard AC. Bhattacharya U. Rodwell MJW.
Semiconductor Science & Technology, vol.11, 1996, pp.1596-600.
******
We report the observation of dynamic localization, absolute negative conductance (ANC) and multiphoton stimulated emission in sequential resonant tunnelling semiconductor superlattice bow-tie antenna coupled to intense terahertz electric fields. Perhaps the most remarkable observation is that with increasing terahertz field strength the conductance near zero d.c. bias decreases towards zero and then becomes negative. The results presented here compare favourably with a model in which virtual states, familiar from nonlinear optics, take a role similar to the unperturbed quantum well states.

“Photon-assisted tunneling in GaAs/AlGaAs superlattices up to room temperature.”
Zeunel S. Allen SJ. Maranowski KD. Gossard AC.
Applied Physics Letters, vol.69, 1996, pp.2689-91.
******
Photon-assisted transport is shown to be a remarkably robust phenomenon in sequential resonant superlattices with a large energy separation between the ground state and the first excited state of the quantum wells. Photon-assisted tunneling involving up to seven photons per tunneling event, stands out very clearly. The one-photon channel is observed up to 300 K. This implies that these superlattices are a gain medium at THz frequencies even at room temperature and potentially important for the future design of THz sources.

“Multiphoton-assisted tunneling, dynamic localization and absolute negative conductance.”
Keay BJ. Allen SJ Jr. Maranowski KD. Gossard AC. Bhattacharya U. Rodwell MJW.
Surface Science, vol.361-362, 20 July 1996, pp.176-80.
******
We report the observation of Absolute Negative Conductance (ANC), multiphoton stimulated emission and dynamical localization in sequential resonant tunneling semiconductor superlattices driven by intense terahertz electric fields. With increasing terahertz field strength the conductance near zero dc bias decreases towards zero and then becomes negative. This is accompanied by new steps and plateaus that are attributed to multiphoton-assisted resonant tunneling between ground states of neighboring quantum wells accompanied by the stimulated emission of a photon.

"Inverse Bloch oscillator: strong terahertz-photocurrent resonances at the Bloch frequency.
Unterrainer K. Keay BJ. Wanke MC. Allen SJ. Leonard D. Medeiros-Ribeiro G. Bhattacharya U. Rodwell MJW.
Physical Review Letters, vol.76, 1996, pp.2973-6.
******
We have observed the inverse Bloch oscillator effect: resonant changes in the current-voltage characteristics of miniband semiconductor superlattices when the Bloch frequency is resonant with a terahertz field and its harmonics. The resonances consist of a peak in the current accompanied by a decrease of the current at the low bias side. At the highest intensities we observe up to a four-photon resonance. This is ananalog of Shapiro steps in a S-I-S junction caused by the AC Josephson effect. The increase of the current is caused by stimulated emission of photons and we can estimate the THz grain of the superlattice from theinduced current at the resonance.

"Transition from classical to quantum response in semiconductor superlattices at THz frequencies"
Zeuner S. Keay BJ. Allen SJ. Maranowski KD. Gossard AC. Bhattacharya U. Rodwell MJW.
Physical Review B-Condensed Matter, vol.53, 1996, pp. R1717-20.
******
The response of a sequential resonant tunneling superlattice to intense THz radiation shows a transition from classical rectification at frequencies below 600 GHz to quantum response above 1 THz. In the quantum regime, the dc current-voltage characteristics show distinct peaks due toabsorption and stimulated emission of up to three THz photons. For sufficiently high ac field strengths the photon-assisted channels dominate the transport, leading to absolute negative conductance near zero bias, and gain just below the Stark splitting of the ground states in adjacent quantum wells. Quantitative agreement with these observations is obtained by invoking photon-assisted tunneling following Tucker, but with an instantaneous I-V free of domain formation.

"Sequential resonant tunneling via photon virtual states in semiconductor superlattices"
Keay BJ. Allen SJ Jr. Kaminski A. Campman KL. Gossard AC. Bhattacharya B. Rodwell MJM. Galan J.
Proceedings of 22nd International Conference on the Physics of Semiconductors. World
Scientific. Part vol.2, 1995, pp.1055-8 vol.2. Singapore.
******
Photon-assisted tunneling is strongly enhanced in bow-tie antenna coupled multiple quantum wells. The I-V characteristics at large terahertz power have steps, plateaus, and NDR structure similar to the static I-V, but are defined by resonant tunneling between photon virtual states and real states.

"Dynamic localization, absolute negative conductance, and stimulated, multiphoton emission in sequential resonant tunneling semiconductor superlattices"
Keay BJ. Zeuner S. Allen SJ Jr. Maranowski KD. Gossard AC. Bhattacharya U. Rodwell MJW.
Physical Review Letters, vol.75, no.22, 27 Nov. 1995, pp.4102-5.
******
We report the first observation of absolute negative conductance and multiphoton stimulated emission in sequential resonant tunneling semiconductor superlattices driven by intense terahertz electric fields. With increasing terahertz field strength the conductance near zero DC bias decreases towards zero and then becomes negative. This is accompanied by new steps and plateaus that are attributed to multiphoton-assisted resonant tunneling between ground states of neighboring quantum wells accompanied by the stimulated emission of a photon.

"Photon-assisted electric field domains and multiphoton-assisted tunneling in semiconductor superlattices.
Keay BJ. Allen SJ Jr. Galan J. Kaminki JP. Campman KL. Gossard AC. Bhattacharya U. Rodwell MJW"
Physical Review Letters, vol.75, 1995, pp.4098-101.
******
We report the first observation of photon-assisted tunneling induced electric field domains, terahertz multiphoton-assisted tunneling, and an oscillatory dependence of the photon induced currents on terahertz electric field strength in semiconductor superlattices. The new structure in the current-voltage (I-V) characteristics-as well as the dependence of the current on terahertz electric field strength compares favorably with a model for the current and electrical field profile in superlattices in which new virtual states serve a role similar to the unperturbed quantum well states.

"Photon-assisted tunneling in a resonant tunneling diode: stimulated emission and absorption in the THz range"
Drexler H. Scott AJS. Allen SJ. Campman KL. Gossard AC.
Applied Physics Letters, vol.67, 1995, pp.2816-18.
******
The dc I-V characteristic of a triple-barrier resonant tunneling diode (RTD) integrated in a bowtie antenna and driven by THz radiation displays up to five additional resonant tunneling channels. These channels appear as additional peaks in the I-V characteristic whose voltage positions vary linearly with frequency in the investigated range between nu =1.0 and 3.THz. We attribute these peaks to photon-assisted tunneling processes corresponding to absorption and stimulated emission of up to three photons. The experiments suggest that such a device can be utilized to detect and generate THz radiation.

"Electrical transport properties of superlattices under intense terahertz electric fields"
Guimaraes PSS. Keay BJ. Kaminski JP. Allen SJ Jr. Hopkins PF. Gossard AC. Florez LT. Harbison JP.
Brazilian Journal of Physics, vol.24, 1994, pp.163-9.
******
We report measurements of the low DC field conductance and the nonlinear IV characteristics of GaAs/AlGaAs multiquantum well superlattices submitted to intense AC electric fields in the terahertz frequency range. The DC conductance exhibits an oscillatory behavior as a function of the terahertz field strength that resembles the zero order Bessel function, J/sub 0/(edE/h(cross) omega), where e, d, and E are the electron charge, superlattice period and AC field strength respectively. The nonlinear DC IV characteristics display new steps and plateaus when the superlattices are subjected to the terahertz fields. The dependency of this new structure in the IV curves on frequency shows that the AC fields introduce new electronic conduction channels via photon mediated sequential tunneling.

"Superlattice transport in intense terahertz electric fields"
Keay BJ. Guimaraes PSS. Kaminski JP. Allen SJ Jr. Hopkins PF. Gossard AC. Florez LT. Harbison JP.

Surface Science, vol.305, 1994, pp.385-8.
******
The low DC field conductance and the nonlinear I-V characteristics of GaAs/Al/sub 0.70/Ga/sub 0.30/As superlattices have been measured in the presence of intense electric fields produced by UCSB's free-electron lasers. The DC conductance exhibits oscillatory behavior as a function of terahertz field strength that resembles the zeroth-order Bessel function, J/sub 0/(edE/sup AC//h(cross) omega), where e, d, and E/sup AC/ are the electron charge, superlattice period and AC field strength, respectively. The I-V characteristics, measured between 600 GHz and 3.1 THz, display new steps and plateaus. The dependence of the new structure of frequency suggests the presence of new conduction channels that are most naturally assigned to photon-mediated sequential tunneling.

"Photon-mediated sequential resonant tunneling in intense terahertz electric fields"
Guimaraes PSS. Keay BJ. Kaminiski JP. Allen SJ Jr. Hopkins PF. Gossard AC. Florez LT. Harbison JP.
Physical Review Letters, vol.70, 1993, pp.3792-5.
******
The authors have measured the current-voltage (I-V) characteristic of semiconductor superlattices in the presence of intense terahertz electric fields produced by free-electron lasers. The nonlinear I-V-curves exhibit new structure that they attribute to photon-mediated sequential resonant tunneling. This tunneling process consists of well to well sequential tunneling into photon sidebands induced by the terahertz electric fields.

Non-linear Terahertz Dynamics

"Subharmonic generation in a driven asymmetric quantum well"
Birnir B. Batista AA. Sherwin MS.
Proceedings of SPIE, vol.3617, 1999, pp.159-63.
******
Subharmonic generation in quantum wells may have important technological applications. Potentially it can be used to produce "squeezed" states of THz radiation. Galdrikian and Birnir (Phys. Rev. Lett 29, 3308 (1996)) derived density matrix dynamical equations for a many-body two-level system of electrons confined in an asymmetric square well. They showed numerically that the electron current density would undergo period-doubling bifurcations and thus produce subharmonics of the laser frequency omega . Their equations are averaged to second order at twice the frequency of the bare two-level system, omega /sub 0/. It is found that at omega =2 omega /sub 0/ the period doubling bifurcation is similar to the one of the Duffing's equation.

"Subharmonic generation in a driven asymmetric quantum well"
Batista AA. Birnir B. Sherwin MS.
Physical Review B-Condensed Matter, vol.61, 2000, pp.15108-13.
******
A realistic model of a doped quantum well heterostructure exhibits a subharmonic signal in the presence of intense far-infrared radiation. Nonlinearity enters the model through the effective potential due to the density of the electrons in the well. Driven at twice the resonant frequency of a "bare" two-level system the electron states undergo a subcritical pitchfork bifurcation. The signature of this nonlinear bifurcation is an emitted subharmonic radiation at half of the frequency of the drive. This nonperturbative response is found by applying the technique of averaging from nonlinear dynamical systems theory to the density matrix dynamical equations, for a many-body two-level system of electrons confined in the asymmetric square well, of Galdrikian and Birnir Phys. Rev. Lett. 29, 3308 (1996). The averaged equations determine the parameter ranges of the subharmonic response and t moderate values of field strength of the drive. Potential technological applications of subharmonic generation include frequency conversion and the production of "squeezed" states of THz radiation.

"Frequency dependence of the third order susceptibility of InAs quantum wells at terahertz frequencies"
Markelz AG. Cerne J. Gwinn EG. Sherwin MS. Brar B. Kroemer H.
Proceedings of 22nd International Conference on the Physics of Semiconductors. World Scientific. Part vol.2, 1995, pp.1193-6 vol.2.
******
The frequency dependence of the large third order susceptibility, chi /sup (3)/(omega , omega , omega , 3 omega), found in InAs quantum wells was studied using third harmonic generation measurements at terahertz frequencies. The frequency dependence of chi /sup (3)/(omega , omega , omega , 3 omega) of an InAs quantum well and of an inversion layer at the surface of an InAs epilayer are nearly identical. The expected roll off of chi /sup (3)/(omega ,

omega , omega , 3 omega) as omega approaches 1/ tau /sub m/ is absent. Instead, chi /sup (3)/(omega , omega , omega , omega) decreases rapidly as omega decreases below 15 cm/sup -1/.

“Nonlinear multiphoton resonances in quantum wells”
Galdrikian B. Birnir B. Sherwin M.
Physics Letters A, vol.203, 1995, pp.319-32.
Netherlands.
******
The periodically driven particle in a box serves as a starting point for the qualitative analysis of nonintegrable systems, and as a simple model of semiconductor quantum wells exposed to intense far-infrared radiation. Classically, the phase space contains chaotic low-momentum trajectories, bounded by a sharp transition to regular motion for high momenta. The quantized system contains invariant states which localize upon classical invariant surfaces. We model the time evolution of the ground state (in the classical system, an ensemble of low-momentum trajectories) under various driving amplitudes and frequencies. Whereas the dynamics of the classical system are governed by the presence of KAM tori, the quantized system also displays sharp, nonperturbative resonances at particular driving parameters. These resonances correspond to the mixing of Floquet states at avoided crossings pation, and the continuum are taken into account.

“Nonlinear quantum dynamics in semiconductor quantum wells”
Sherwin MS. Craig K. Galdrikian B. Heyman J. Markelz A. Campman K. Fafard S. Hopkins PF. Gossard A.
Physica D, vol.83, 1995, pp.229-42.
******
We discuss recent measurements of the nonlinear response of electrons in wide quantum wells driven by intense electromagnetic radiation at terahertz frequencies. The theme is the interplay of quantum mechanics, strong periodic driving, the electron-electron interaction and dissipation. We discuss harmonic generation from an asymmetric double quantum well in which the effects of dynamic screening are important. Measurements and theory are found to be in good agreement. We also discuss intensity-dependent absorption in a 400AA square quantum well. A new nonlinear quantum effect occurs, in which the frequency at which electromagnetic radiation is absorbed shifts to the red with increasing intensity. The preliminary experimental results are in agreement with a theory by Zaluzny.

“Subcubic power dependence of third-harmonic generation for in-plane, far-infrared excitation of InAs quantum wells.
Markelz AG. Asmar NG. Gwinn EG. Sherwin MS. Nguyen C. Kroemer H.
Semiconductor Science & Technology, vol.9, no.5S, May 1994, pp.634-7.
******
Large third-order, free-carrier nonlinear susceptibilities, X/sup (3)/ (to approximately 0.2 esu), and subcubic dependence of the third-harmonic power on the incident intensity, have been observed between 19 cm/sup -1/ and 23 cm/sup -1/ for InAs/AlSb quantum wells with electron sheet densities between 2.5*10/sup 12/ cm/sup -2/. and 8*10/sup 12/ cm/sup -2/. We find that the transmission of the fundamental, and the samples' DC conductivity, decrease with increasing incident intensity, indicating a large rise in the scattering rate. Using the intensity-dependent transmission to account for absorption in the sample is not sufficient to recover a cubic power law for the third-harmonic intensity. In addition, given the increased scattering rate indicated by the conductivity data, the bulk free-carrier X/sup (3)/ due to non-parabolicity should decrease dramatically with increasing fundam served third-harmonic response.

“Self-consistent Floquet states for periodically driven quantum wells.
Galdrikian B. Sherwin M. Birnir B.
Physical Review B-Condensed Matter, vol.49, 1994, pp.13744-9.
******
We have developed a nonperturbative method to compute the dynamics of electrons in quantum wells driven by oscillating electric fields. Floquet theory enables us to compute, in the local-density approximation, solutions of the Schrodinger equation for zero temperature which are self-consistent and for which the density is periodic in time. The method is demonstrated by computing harmonic generation from a tilted square well, which agrees with perturbation theory, and second-harmonic emission from an Al/sub 0.3/Ga/sub 0.7/As heterojunction, which agrees with recent experiments of Bewley et al.

“Resonant harmonic generation and dynamic screening in a double quantum well”
Heyman JN. Craig K. Galdrikian B. Sherwin MS. Campman K. Hopkins PF. Fafard S. Gossard AC.
Physical Review Letters, vol.72, no.14, 4 April 1994, pp.2183-6. USA.
******
Second- and third-harmonic generation are observed in a semiconductor heterostructure which approximates a two-state system with an 11-meV level spacing. A resonance in the second- (third-) harmonic generation is found when the depolarization-shifted infrared absorption peak is Stark tuned through 2 (3) times the pump frequency. These resonances are thus associated with the depolarization-shifted, and not the bare, intersubband energy. Data are analyzed with a theory of second-harmonic generation including dynamic screening. Saturation is observed at pump intensities [right angle bracket]10 kW/cm/sup 2/.

“Giant third-order nonlinear susceptibilities for in-plane far-infrared excitation of single InAs quantum wells”
Markelz AG. Gwinn EG. Sherwin MS. Nguyen C. Kroemer H. Solid-State Electronics, vol.37, 1994, pp.1243-5.
******
Third-order, free-carrier nonlinear susceptibilities, chi /sup (3)/, have been measured between 19 and 23 cm/sup -1/ for three InAs/AlSb quantum wells with sheet densities between 2.5*10/sup 12/ cm/sup -2/ and 8*10/sup 12/ cm/sup -2/. We find that these wells are strongly nonlinear at far-infrared frequencies: odd harmonics ninth order have been observed at high incident intensities, and the peak value of chi /sup (3)/ reaches ~1 esu. This is several orders of magnitude larger than previously reported values for chi /sup (3)/ in bulk n-GaAs (10/sup -4/ esu) (1986) and in polyacetylene (10/sup -7/ esu) (1992). The large magnitude of chi /sup (3)/ is attributed to the high carrier density in the InAs wells, and to the strong non-parabolicity of the conduction band in InAs. However, the free-carrier chi /sup (3)/ for bulk InAs predicts a density-dependence different from that observe ve response. We find that the anisotropy of chi /sup (3)/ displays the expected 4-fold symmetry.

“Far-infrared second-harmonic generation in GaAs/Al/sub x/Ga/sub 1-x/As heterostructures: perturbative and nonperturbative response”
Bewley WW. Felix CL. Plombon JJ. Sherwin MS. Sundaram M. Hopkins
PF. Gossard AC. Physical Review B-Condensed Matter, vol.48, 1993, pp.2376-90.
******
The authors report measurements of far-infrared (FIR) harmonic generation from GaAs/Al/sub x/Ga/sub 1-x/As heterostructures. The samples studied were a modulation-doped Al/sub 0.3/Ga/sub 0.7/As/GaAs heterojunction and a sample with ten modulation-doped half-parabolic quantum wells. The samples were driven with intense far-infrared radiation from a molecular gas laser at 29.5 cm/sup -1/ and the University of California-Santa Barbara free-electron laser at 51.3 cm/sup -1/. The FIR radiation was polarized parallel to the growth direction. Second harmonics of the FIR were detected from both the semi-insulating GaAs substrate and from the confined electrons. For the heterojunction sample, the second-harmonic power generated by the electrons depended quadratically on fundamental power at low power, as expected from time-dependent perturbation theory. However, this dependence became subq were also ionized from the heterojunction and half-parabolic wells. For the heterojunction at f=29.5 cm/sup -1/ in the perturbative regime, the surface second-order susceptibility was computed to be chi /sub S//sup (2)/=1.0+or-0.75*10/sup -8/ esu/sup -1/ cm/sup 3/. This value agrees, within experimental error, with a simple model of the heterojunction as a triangular quantum well. The second-order polarizability of a conduction electron in the heterojunction is nine orders of magnitude larger than that of a valence electron in pure GaAs.

“Nonperturbative resonances in periodically driven quantum wells”
Birnir B. Galdrikian B. Grauer R. Sherwin M.
Physical Review B-Condensed Matter, vol.47, 1993,pp.6795-8.
******
Energy absorption characteristics are computed for a classical and a quantum model of an infinite square well, as a function of driving amplitude and frequency. Nonperturbative resonances are observed corresponding to the replacement of states localized in phase space by more extended states. Their presence is predicted by avoided crossings in the quasienergy spectrum of the Floquet operator. The conditions under which these resonances occur can be realized in experiments on GaAs/Al/sub x/Ga/sub 1-x/As quantum wells in intense far-infrared radiation.

“Nonlinear response of quantum-confined electrons in nonparabolic subbands”
Markelz AG. Gwinn EG.
Journal of Applied Physics, vol.80, 1996, pp.2533-5.

******
We show that quantum confinement can dramatically alter the density-dependence of the third-order susceptibility, chi /sub NP//sup (3)/, that arises from band nonparabolicity. Our results predict an oscillatory dependence of the efficiencies for third-harmonic generation and four-wave mixing on the subband occupation of quantum wells, and for narrow wells with high charge densities predict an enhancement over the bulk susceptibility. We also make a simple estimate of the fields required to saturate this nonparabolicity contribution to chi /sup (3)/. We discuss these results in light of recent experiments on third-harmonic generation from narrow-gap quantum wells at frequencies of ~1 THz, and show that nonparabolicity may not be the only nonlinearity contributing to the large chi (3) observed.

"Frequency dependence of the third order susceptibility of InAs quantum wells at terahertz frequencies.
Markelz AG. Cerne J. Gwinn EG. Sherwin MS. Brar B. Kroemer H.
Proceedings of 22nd International Conference on the Physics of Semiconductors, World Scientific Singapore. Part vol.2, 1995, pp.1193-6.
******
The frequency dependence of the large third order susceptibility, chi /sup (3)/(omega , omega , omega , 3 omega), found in InAs quantum wells was studied using third harmonic generation measurements at terahertz frequencies. The frequency dependence of chi /sup (3)/(omega , omega , omega , 3 omega) of an InAs quantum well and of an inversion layer at the surface of an InAs epilayer are nearly identical. The expected roll off of chi /sup (3)/(omega , omega , omega , 3 omega) as omega approaches 1/ tau /sub m/ is absent. Instead, chi /sup (3)/(omega , omega , omega , omega) decreases rapidly as omega decreases below 15 cm/sup -1/

"Terahertz harmonic generation from Bloch-oscillating superlattices in quasi-optical arrays."
Wanke MC. Scott JS. Allen SJ. Maranowski KD. Gossard AC.,
Proceedings of SPIE, vol.3617, 1999, pp.148-58.
******
We explored harmonic generation by Bloch oscillation in miniband superlattices driven by intense THz radiation from the UCSB free electron lasers, as a function of both THz intensity and applied DC bias. To accomplish this we integrated µm size superlattice mesas in aquasi-optical array which amplified a plane wave incident normal to the array and coupled it into the growth direction of the superlattice. We were able to successfully measure both second and third harmonic generation quantitatively. The harmonics are compared to a quasi-classi calpicture of Bloch oscillation.

"Third harmonic generation by Bloch-oscillating electrons in a quasioptical array."
Ghosh AW. Wanke MC. Allen SJ. Wilkins JW.
Applied Physics Letters, vol.74, 1999, pp.2164-6.
******
We compute the third harmonic field generated by Bloch-oscillating electrons in a quasioptical array of superlattices under THz irradiation. The third harmonic power transmitted oscillates with the internal electric field, with nodes associated with Bessel functions in eEd/h(cross) omega . The nonlinear response of the array causes the output power to be a multivalued function of the incident laser power. The output can be optimized by adjusting the frequency of the incident pulse to match one of the Fabry-Perot resonances in the substrate. Within the transmission-line model of the array, the maximum conversion efficiency is 0.1%.

"Frequency doubling and tripling of terahertz radiation in a GaAs/AlAs superlattice due to frequency modulation of Bloch oscillations."
Winnerl S. Schomburg E. Brandl S. Kus O. Renk KF. Wanke MC. Allen SJ. Ignatov AA. Ustinov V. Zhukov A. Kop'ev PS.,
Applied Physics Letters, vol.77, no.9, 28 Aug. 2000, pp.1259-61.
******
We report on frequency doubling and tripling of THz radiation in a voltage-biased GaAs/AlAs superlattice. By use of a corner cube antenna system, radiation from the Santa Barbara free-electron laser (frequency 0.7 THz) was guided into a superlattice mesa element and the second and third harmonic were coupled out of the mesa. Without bias only radiation of the third harmonic was generated, while the biased superlattice emitted radiation of both the second and third harmonic. We attribute the harmonic generation to frequency modulation of damped Bloch oscillations of the miniband electrons in the superlattice.

"Subcubic power dependence of third-harmonic generation for in-plane, far-infrared excitation of InAs quantum wells"

Markelz AG. Asmar NG. Gwinn EG. Sherwin MS. Nguyen C. Kroemer H.
Semiconductor Science & Technology, vol.9, 1994, pp.634-7.
******
Large third-order, free-carrier nonlinear susceptibilities, X/sup (3)/ (to approximately 0.2 esu), and subcubic dependence of the third-harmonic power on the incident intensity, have been observed between 19 cm/sup -1/ and 23 cm/sup -1/ for InAs/AlSb quantum wells with electron sheet densities between 2.5*10/sup 12/ cm/sup -2/. and 8*10/sup 12/ cm/sup -2/. We find that the transmission of the fundamental, and the samples' DC conductivity, decrease with increasing incident intensity, indicating a large rise in the scattering rate. Using the intensity-dependent transmission to account for absorption in the sample is not sufficient to recover a cubic power law for the third-harmonic intensity. In addition, given the increased scattering rate indicated by the conductivity data, the bulk free-carrier X/sup (3)/ due to non-parabolicity should decrease dramatically with increasing fundam served third-harmonic response.

"Nonlinear dynamics in far-infrared driven quantum-well intersubband transitions"
Batista AA. Tamborenea PI. Birnir B. Sherwin MS. Citrin DS.
Physical Review B-Condensed Matter, vol.66, 2002, pp.195325-1-12.
******
We study the effect of many-body interactions on the collective response of confined electrons in doped quantum-well (QW) heterostructures to intense far-infrared radiation. Absorption line shapes are computed both by numerically integrating the equations of motion and by using the appropriately time-averaged equations. For a two-subband double-QW system, optical bistability and period-doubling bifurcations are observed and their parameter range of activity is given. For a three-subband asymmetric triple-QW system driven at omega approximately=E/sub 2/-E/sub 0/, Hopf bifurcations occur which generate a strong response at a frequency incommensurate with the drive frequency or any natural frequency of the system.

"Third harmonic generation in a GaAs/AlGaAs superlattice in the Bloch oscillator regime."
Wanke MC. Allen SJ. Maranowski K. Medeiros-Ribeiro G. Gossard A. Petroff P.
Proceeedings 23rd International Conference on the Physics of Semiconductors. World Scientific. Part vol.3, 1996, pp.1791-4 vol.3.
******
A GaAs/AlGaAs superlattice driven at 700 GHz exhibits third harmonic generation with a non-monotonic power dependence. Comparison is made with a semi-classical model for Bloch oscillations.

"Third harmonic generation in a GaAs/AlGaAs superlattice in the Bloch oscillator regime."
Wanke MC. Markelz AG. Unterrainer K. Allen SJ. Bhatt R.
Proceeding of Hot Carriers in Semiconductors. Plenum Press. 1996, pp.161-3.
******
A GaAs/AlGaAs superlattice driven at 600 GHz exhibits strong, power dependent third harmonic generation. Conversion efficiency up to 0.1% was observed. The power dependence agrees semi-quantitatively with a simple model describing Bloch oscillations driven by a strong THz electric field.

"Giant third-order nonlinear susceptibilities for in-plane far-infrared excitation of single InAs quantum wells"
Markelz AG. Gwinn EG. Sherwin MS. Nguyen C. Kroemer H.
Solid-State Electronics, vol.37, no.4-6, 1994, pp.1243-5.
******
Third-order, free-carrier nonlinear susceptibilities, chi /sup (3)/, have been measured between 19 and 23 cm/sup -1/ for three InAs/AlSb quantum wells with sheet densities between 2.5*10/sup 12/ cm/sup -2/ and 8*10/sup 12/ cm/sup -2/. We find that these wells are strongly nonlinear at far-infrared frequencies: odd harmonics ninth order have been observed at high incident intensities, and the peak value of chi /sup (3)/ reaches ~1 esu. This is several orders of magnitude larger than previously reported values for chi /sup (3)/ in bulk n-GaAs (10/sup -4/ esu) (1986) and in polyacetylene (10/sup -7/ esu) (1992). The large magnitude of chi /sup (3)/ is attributed to the high carrier density in the InAs wells, and to the strong non-parabolicity of the conduction band in InAs. However, the free-carrier chi /sup (3)/ for bulk InAs predicts a density-dependence different from that observe ve response. We find that the anisotropy of chi /sup (3)/ displays the expected 4-fold symmetry.

"Saturation spectroscopy and electronic-state lifetimes in a magnetic field in InAs/Al/sub x/Ga/sub 1-x/Sb single quantum wells"

Singh SK. McCombe BD. Kono J. Allen SJ Jr. Lo I. Mitchel WC. Stutz CE.
Physical Review B-Condensed Matter, vol.58, 1998, pp.7286-91.
******
Saturation spectroscopy of electronic states in InAs/Al/sub x/Ga/sub 1-x/Sb single-quantum-well structures has been carried out with the UCSB free-electron laser. An effective Landau-level lifetime is extracted from the cyclotron-resonance (CR) saturation results on a semiconducting sample (x=0.5) with the help of an n-level rate equation model. The effective lifetime shows strong oscillations (greater than an order of magnitude) with laser frequency with minima shifted to higher frequencies than given by the simple parabolic magnetophonon resonance condition due to large nonparabolicity in the InAs conduction band. Similar saturation studies of two lines (the X line and CR) in a "semimetallic" sample (x=0.1) show markedly different effective lifetimes, demonstrating that the two lines are of different origin.

Terahertz Materials Physics

"Terahertz circular dichroism spectroscopy of biomolecules."
Jing Xu. Galan J. Ramian G. Savvidis P. Scopatz A. Birge RR. Allen SJ. Plaxco K.
SPIE, vol.5268, no.1, 2003, pp.19-26.
******
Biopolymers such as proteins, DNA and RNA fold into large, macromolecular chiral structures. As charged macromolecules, they absorb strongly in the terahertz due to large-scale collective vibrational modes; as chiral objects, this absorption should be coupled with significant circular dichroism. Terahertz circular dichroism (TCD) is potentially important as a biospecific sensor, unobscured by spectral features related to a biological material. We have constructed atomistic simulations and elastic continuum models of TCD. These models estimate the magnitude of the TCD and the relation between TCD spectroscopic signatures (zero crossings) and the structure, charge distribution and mechanical properties of biomaterials. A broad band TCD spectrometer based on a polarizing interferometer is developed to explore TCD in biomolecules in aqueous solution. Preliminary results on TCD in lysozyme in water at several terahertz frequencies is presented.

"Spectroscopic study of Kondo insulator YbB/sub 12/ using a free electron laser"
Ohta H. Nanba T. Lehnert K. Allen SJ. Motokawa M. Iga F. Kasaya M.
Journal of Magnetism & Magnetic Materials, vol.177-181, 1998, pp.341-2.
******
The bolometric response of Kondo insulator YbB/sub 12/ has been studied for the first time in the energy region from 4 to 130 cm/sup -1/ at 1. K using the free-electron laser (FEL) at University of California at Santa Barbara. The increases of response are observed at around 50 and 130 cm/sup -1/ and they are discussed in connection with the gap structure proposed by Sugiyama et al. previously.

"Terahertz excitation, transport, and spectroscopy of an AFM-defined quantum dot"
Qureshi N. Allen SJ. Kamiya I. Nakamura Y. Sakaki H.
Proceedings of SPIE, vol.3617, 1999, pp.133-6.
******
We have investigated the terahertz photoresponse of a single semiconductor quantum dot, electrostatically defined by a sharp conducting atomic force microscope tip in contact with a resonant tunneling diode structure. The quantum dot is excited by radiation from a free electron laser in experiments both at room temperature and at cryogenic temperatures. Pronounced resonant tunneling features and classical rectification at frequencies from 0.3 to 3 THz are observed in the I-V curves of these devices. These results demonstrate a novel approach to achieving terahertz excitation and studying transport in quantum dots.

"Imaging and probing electronic properties of self-assembled InAs quantum dots by atomic force microscopy with conductive tip."
Tanaka I. Kamiya I. Sakaki H. Qureshi N. Allen SJ Jr. Petroff PM.
Applied Physics Letters, vol.74, 1999, pp.844-6.
******
Atomic force microscopy with a conductive probe has been used to study both the topography and the electronic properties of 10-nm-scale self-assembled InAs quantum dots (QDs) grown by molecular beam epitaxy on n-type GaAs. The current flowing through the conductive probe normal to the sample surface is measured for imaging local conductance, while the deflection of cantilever is optically detected for disclosing geometrical structure. The conductance on InAs QDs is found to be much larger than that on the wetting layer, allowing imaging of QDs

through measurements of local current. We attribute this change in conductance to the local modification of surface band bending associated with surface states on InAs QD surface. Mechanisms of electron transport through QDs are discussed based on current-voltage characteristics measured on QDs of various sizes.

"Terahertz excitation of AFM-defined room temperature quantum dots."
Qureshi N. Scott JS. Allen SJ Jr. Reddy M. Rodwell MJW. Nakamura Y. Tanaka I. Noda T. Kamiya I. Sakaki H.
Physica E, vol.2, 1998, pp.701-3.
******
The terahertz photoresponse of a single semiconductor quantum dot is measured at room temperature. Pronounced resonant tunneling and a rectified response at frequencies from 0.6 to 3 THz are observed in the I-V curve of the submicron device. We use this to demonstrate a novel approach to the study of quantum dots, in which a submicron resonant tunneling device is electrostatically defined using a conducting atomic force microscope (AFM) tip. In addition, the conducting AFM tip electrically contacts the device and serves as an antenna to couple far-infrared radiation into the dot.

"Terahertz-frequency intraband absorption in semiconductor quantum dot molecules"
Boucaud P. Gill KS. Williams JB. Sherwin MS. Schoenfeld WV. Petroff PM.
Physica Status Solidi B-Basic Research, vol.224, 2001, pp.443-6.
******
We have studied THz absorption of samples containing two layers of self-aligned, self-assembled InAs quantum dots separated by a thin GaAs barrier. The electronic population of the vertically-coupled dots is controlled by an applied bias between a metal gate and a doped layer beneath the dots. Under flat band conditions, an absorption peak is observed near 10 meV (2.4 THz). The absorption is attributed to the intersublevel transition between the quantum mechanically split bonding and antibonding levels in the quantum dot molecules. This absorption can be bleached under high excitation intensity delivered by a free-electron laser. The saturation intensity is found to be of order 1 W cm/sup -2/. A lower limit for the relaxation time T/sub 1/ of the order of 30 ps is deduced from the saturation intensity.

"Far-infrared excitations in InAs quantum wires".
Kono J. Peralta XG. Cerne J. Allen SJ Jr. Sakaki H. Sugihara T. Sasa S. Inoue M.
Proceedings 23rd International Conference on the Physics of Semiconductors. World Scientific. Part vol.2, 1996, pp.1173-6 vol.2.
******
We present results of far-infrared (FIR) laser magneto-spectroscopy of etched InAs quantum wires whose widths range from 100 to 630 nm. The photoconductivity technique was employed in conjunction with intense FIR radiation from the UCSB free-electron lasers. At high FIR powers a frequency-insensitive temperature modulation of the electron gas occurred, resulting in pronounced photoresponse oscillations vs magnetic field, B. At low FIR powers we observed resonant peaks due to magneto-plasmon excitations, whose amplitude shows strong polarization-dependence. The high and low power results provide, in a complementary fashion, an excellent method to characterize quasi-one-dimensional states in the wires.

"Terahertz photoresponse of quantum wires in magnetic fields."
Kono J. Nakamura Y. Peralta XG. Cerne J. Allen SJ Jr. Akiyama H. Sakaki H. Sigihara T. Sasa S. Inoue M.
Superlattices & Microstructures, vol.20, no.3, 1996, pp.383-7.
******
We have investigated the terahertz photoresponse of quantum wires in high magnetic fields, employing intense far-infrared (FIR) radiation from the UCSB Free-Electron lasers. Both GaAs-based and InAs-based quantum wires, with widths ranging from 50 nm to 1 mu m, were studied. At high FIR power we observed Shubnikov-de Haas type oscillations in photoresponse versus magnetic field, B, resulting from non-resonant electronic heating; the oscillations were much more pronounced than those in resistance versus b. At low FIR power we observed resonant peaks due to magnetoplasmon excitations, whose strength shows strong polarization-dependence and whose energy extrapolates to a finite value at zero b. These results provide a powerful tool for characterizing 1D electronic states in quantum wires.

"Plasmons in a superlattice in a parabolic quantum well."
Sundaram M. Allen SJ Jr. Geller MR. Campman KL. Gossard AC.
Applied Physics Letters, vol.67, no.21, 20 Nov. 1995, pp.3165-7. USA.

******

Well-defined plasma oscillations are observed in a superlattice miniband even though the Fermi energy lies in the minigap. Despite the complex band structure, the resonance shows a remarkable insensitivity to changes in the number of electrons in the parabolic well in which the superlattice is placed, a feature of the generalized Kohn theorem that is expected only in the limit that the Fermi energy is near the bottom of the lowest miniband.

"Intraminiband plasmons in a superlattice within a parabolic well"
Campman KL. Sundaram M. Allen SJ Jr. Gossard AC.
Superlattices & Microstructures, vol.15, no.2, 1994, pp.141-4. UK.
******

A well defined collective plasma resonance corresponding to electrons tunneling back and forth through superlattice barriers is observed in a series of modulation doped AlGaAs heterostructures containing a superlattice within a parabolic potential. Due to occupation of a large fraction of the miniband, the resonance frequency decreases strongly with increasing superlattice barrier thickness.

"Infrared absorption of holes in a parabolic quantum well."
Sundaram M. Allen SJ Jr. Geller R. Hopkins PF. Campman KL. Gossard AC.
Applied Physics Letters, vol.65, 1994, pp.2226-8.
******

We observe the infrared absorption of holes in a wide graded Al/sub x/Ga/sub 1-x/As parabolic quantum well to be at a single frequency, independent of the number of holes in the well. The resonant absorption frequency appears to be determined by the light hole mass, not the heavy hole mass.

"Low-temperature carrier distributions in wide quantum wells of different shapes from capacitance-voltage measurements"
Sundaram M. Allen SJ Jr. Gossard AC.
Journal of Applied Physics, vol.76, 1994, pp.1003-7.
******

The carrier distributions in modulation-doped wide graded quantum wells that a measurement of the capacitance C between a surface gate and an ohmic contact to the carriers as a function of the applied bias V would yield are calculated. These capacitance-voltage (C-V) distributions are found to agree inexactly, but closely, with the calculated true carrier distributions. Density modulation features, induced by superlattices or by abrupt changes in the curvature of band-gap grading, are strikingly reproduced. Electron distributions extracted from actual measurements on a wide parabolic well and on a parabolic well with superimposed superlattice are in good agreement with theory. For the case of the parabolic well, the occupancy of a finite number of subbands is manifested as structure in the C-V distributions.

"Infrared spectroscopy of lateral-density-modulated 2DES in InAs/AlSb quantum wells"
Sundaram M. Allen SJ Jr. Nguyen C. Brar B. Jayaraman V. Kroemer H.
Solid-State Electronics, vol.37, 1994, pp.1293-5.
******

In infrared transmission experiments through a two-dimensional electron system with substantial lateral density modulation in an InAs quantum well, we directly observe plasmon absorption without the mediating help of a surface metallic grating. The plasmon frequency is determined by the average density, and its strength by the amplitude of the density modulation. It disperses in a magnetic field in predicted fashion.

"Tunable far infrared absorption in logarithmically graded quantum wells"
Hopkins PF. Sundaram M. Campman KL. Bellomi G. Yuh EL. Allen SJ Jr. Gossard AC.
Solid-State Electronics, vol.37, 1994, pp.1285-8.
******

Compositional grading in the growth direction z of a GaAs/Al/sub x/Ga/sub 1-x/As heterostructure is used to simulate a potential well of the form V(z)=-a/sup -2/ln (abz+1)+zb/a, where a and b are constants. Using both a front gate and an epitaxially grown back gate, we observe a large Stark shift from 35 to 125 cm/sup -1/ in the far infrared collective electronic resonant response by moving the electron gas through the asymmetric well.

"Dissipation of intersubband plasmons in wide quantum wells"
Williams JB. Sherwin MS. Maranowski KD. Gossard AC
Physical Review Letters, vol.87, 2001, pp.037401/1

******

This Letter reports detailed measurements of the dissipation times tau /sub d/ of ~10 meV intersubband (ISB) plasmons, and of the (single-particle) transport lifetimes tau /sub mu /, in a remotely doped 40 nm GaAs quantum well. Introduced here as the time for ISB plasmons to dissipate into other modes of the electron gas, tau /sub d/ is deduced from the homogeneous ISB absorption linewidth, measured as a function of sheet concentration and perpendicular dc electric field. Modeling in this and the next Letter [C.A. Ullrich and G. Vignale, Phys. Rev. Lett. 87, 037402 (2001)] indicates that scattering from rough interfaces dominates tau /sub d/, while scattering from ionized impurities dominates tau /sub mu /.

"Terahertz-frequency electronic coupling in vertically coupled quantum dots"
Boucaud P. Williams JB. Gill KS. Sherwin MS. Schoenfeld WV. Petroff PM.
Applied Physics Letters, vol.77, 2000, pp.4356-8.
******

We have studied terahertz absorption of samples containing two layers of self-aligned, self-assembled InAs quantum dots separated by a thin GaAs barrier. The vertically coupled dots were charged with electrons by applying a voltage bias between a metal gate and a doped layer beneath the dots. For a positive gate bias corresponding to flatband conditions, an absorption peak was observed near 10 meV (2.4 THz). The absorption is attributed to the inhomogeneously broadened transition between the quantum mechanically split levels (bonding and antibonding states) in the vertically coupled quantum dots.

"Linewidth and dephasing of THz-frequency collective intersubband transitions in a GaAs/AlGaAs quantum well."
Williams JB. Sherwin MS. Maranowski KD. Kadow C. Gossard AC.
Physica E, vol.7, 2000, pp.204-7.
******

Terahertz-frequency intersubband (ISB) transitions in semiconductor quantum wells are of interest due to the potential for making devices that operate at THz frequencies, and the influence of many-body interactions on the intersubband dynamics. We present measurements of the linear absorption linewidth of ISB transitions in a single 40 nm delta-doped GaAs/Al/sub 0.3/Ga/sub 0.7/As square quantum well, with a transition energy of order 10 meV (3 THz). Separate back- and front-gates allow independent control of charge density (0.1-1*10/sup 10/ cm/sup -2/) and DC bias (-2.5-0.5 mV/nm). A picture of scattering of the intersubband plasmon into single-particle excitations qualitatively explains the DC bias dependence of the line-width data.

"Linewidth of THz intersubband transitions in GaAs/AlGaAs quantum wells"
Williams JB. Sherwin MS. Maranowski KD. Kadow C. Gossard AC.
Proceedings of Spie, vol.3617, 1999, pp.126-32.
******

Terahertz-frequency intersubband transitions in semiconductor quantum wells are of interest due to the potential for making devices which operate at THz frequencies, and the importance of many body interactions on the intersubband dynamics. We present measurements of the linear absorption linewidth of ISB transitions in a single 40 nm delta-doped GaAs/Al/sub 0.3/Ga/sub 0.7/As square quantum well, with a transition energy of order 10 meV. Separate back-and front-gates allow independent control of charge density and DC bias. The absorption linewidth is proportional to the dephasing rate of the collective excitation. In order to examine the dephasing dynamics at THz frequencies, we have begun a detailed measurement of the ISB absorption versus charge density.

"Measurements of far-infrared intersubband absorption linewidths in GaAs/AlGaAs quantum wells as a function of temperature and charge density"
Williams JB. Craig K. Sherwin MS. Campman K. Gossard AC.
Physica E, vol.2, 1998, pp.177-80.
******

Intersubband transitions in doped quantum wells are of fundamental scientific interest, as well as technological interest for potential devices. One of the important characteristics of the transitions is their linewidth. We present the results of linear absorption spectroscopy on a coupled double asymmetric QW structure. Using a backgated sample, we can independently vary the charge density and DC field at the well. The absorption lines appear to be homogeneously broadened. The lines appear to become lifetime broadened for temperatures above 70 K.

"Quantum confinement without walls"
Tsujino S. Allen SJ. Thomas M. Eckhause T. Gwinn E. Rufenacht M. Zhang JP. Speck J. Sakaki H.

Superlattices & Microstructures, vol.27, no.5-6, 2000, pp.469-72.
******
We explore and demonstrate quantum confinement without walls in metal-clad InAs quantum wells. We observed intersubband absorption from confined states in InAs clad with Al, Sb, Nb, W, Pt, Ag, Au, Ti or In. We found that using this novel method, we can explore the physics and chemistry at the metal-semiconductor interface; reflection, autoionization, well-width fluctuation and interface reaction.

"Logarithmically graded quantum well far-infrared modulator"
Hopkins PF. Campman KL. Bellomi G. Gossard AC. Sundaram M. Yuh EL. Gwinn EG.
Applied Physics Letters, vol.64, 1994, pp.348-50.
******
We have designed and fabricated a remotely doped "logarithmic" potential well intended to have a tunable, narrow band absorption at far-infrared frequencies. A surface gate, epitaxially grown backgate, and contact to the electron gas in the quantum well allow independent control of the absorption frequency and the integrated absorption strength. The resonance frequency is dominated by the well curvature at the potential minimum and can be Stark shifted from omega /2 pi c=35 cm/sup -1/ to a frequency of 125 cm/sup -1/ by moving the electron gas through the asymmetric well.

Terahertz Non-equilibrium dynamics

"Absorption saturation studies of Landau levels in quasi-two-dimensional systems."
Muratov LS. Stockman MI. Pandey LN. George TF. Li WJ. McCombe BD. Kaminski JP. Allen SJ. Schaff WJ.
Superlattices & Microstructures, vol.21, 1997, pp.501-8.
******
We report the first far-infrared linear and non-linear (saturation) magneto absorption experiments of coupled subband-Landau level excitations in a series of modulation-doped double-coupled multiple quantum-well (MQW) structures. Non-linear spectroscopy is carried out with a free electron laser. A plot of energy versus magnetic field for 4 laser lines at low intensity and high intensity is compared with linear (Fourier transform) spectroscopy at low and high temperatures. An exact numerical solution of the Schrodinger equation for this coupled system is also obtained and compared with experiments. Results show that the feature observed at high laser intensity and high temperature is due to transitions from the 1st-excited state of the coupled system to the higher excited states. Based on this, a simple 2-level model is developed, and with a layer-by-layer analysis for MQW systems

"Free electron laser saturation spectroscopy of neutral donors and negative donor ions confined in GaAs/AlGaAs quantum wells.",
Ryu SR. Herold G. Kono J. Salib M. McCombe BD. Kaminski J. Allen SJ Jr.
Superlattices & Microstructures, vol.21, 1997, pp.241-6.
****** Saturation of the D/sup 0/ 1s-2p/sup +/ transition, the D/sup -/-singlet transition and CR has been studied in donor (Si)-doped GaAs/AlGaAs multiple-quantum-well samples by magneto-transmission and magneto-photoconductivity measurements with the UCSB free electron laser. Effective lifetimes of the D/sup 0/ 1s-2p/sup +/ transition were found to vary systematically with laser frequency, decreasing from 62 ns at 8cm/sup -1/ to 3 ns at 124 cm/sup -1/. The absorption coefficient of the D/sup -/-singlet transition initially increased by up to 40% and showed complete quenching at higher laser powers.

"Saturation spectroscopy of electronic states in a magnetic field in InAs/Al/sub x/Ga/sub 1-x/Sb single quantum wells."
Singh SK. McCombe BD. Kono J. Allen SJ Jr. Lo I. Mitchel WC. Stutz CE.
Physica E, vol.2,1998, pp.204-8.
******
We have carried out saturation spectroscopy of cyclotron resonance in a semiconducting InAs/Al/sub 0.5/Ga/sub 0.5/Sb single quantum well using the UCSB free electron laser and have extracted an effective Landau level lifetime using an n-level rate equation model. The effective lifetime shows strong oscillations ([right angle bracket] an order of magnitude) with frequency. Minima are shifted to higher frequencies than those given by the simple parabolic magnetophonon resonance condition due to large nonparabolicity in the InAs conduction band. We have also used this technique to investigate the origins of two lines: the X-line and cyclotron resonance in a "semimetallic" InAs/Al/sub 0.1/Ga/sub 0.9/Sb single quantum-well structure. Results show that the two lines are of different origin.

“Saturation spectroscopy of hot carriers in coupled double quantum well structures”
Li WJ. McCombe BD. Kaminski JP. Allen SJ. Stockman MI. Muratov LS. Pandey LN. George TF. Schaff WJ.
Semiconductor Science & Technology, vol.9, 1994, pp.630-3.
******
We report the first combination of far-infrared linear and nonlinear (saturation) magnetoabsorption experiments on coupled subband Landau level excitations in a series of modulation-doped multiple coupled double quantum well (MCDQW) structures. Linear spectroscopy was carried out with a Fourier transform spectrometer over a range of temperature, and saturation spectroscopy was carried out with the free electron laser at UC Santa Barbara. Based on theoretical analysis, an electron lifetime of approximately 1.2 ns was obtained.

“Energy relaxation rate of terahertz-driven quasi-two-dimensional electrons”.
Asmar NG. Markelz AG. Gwinn EG. Campman KL. Gossard AC.
Proceedings of 22nd International Conference on the Physics of Semiconductors. World Scientific. Part vol.2, 1995, pp.1147-8
******
We use the DC conductivity of quasi-two-dimensional electrons driven by steady-state, intense terahertz (THz) fields to obtain the rate of electron energy loss to LO phonons. We find a drop in the LO phonon emission time near 0.5 THz, indicating a crossover in electron-LO phonon scattering that weakens the hot-phonon bottleneck.

“Temperature of quasi-two-dimensional electron gases under steady-state terahertz drive”
Asmar NG. Cerne J. Markelz AG. Gwinn EG. Sherwin MS. Campman KL. Gossard AC.
Applied Physics Letters, vol.68, 1996, pp.829-31.
******
We use photoluminescence to study the time-average energy distribution of electrons in the presence of strong steady-state drive at terahertz (THz) frequencies, in a modulation-doped 125 AA AlGaAs/GaAs square well that is held at low lattice temperature T/sub L/. We find that the energy distribution can be characterized by an effective electron temperature, T/sub e/([right angle bracket]T/sub L/), that agrees well with values estimated from the THz-illuminated, dc conductivity. This agreement indicates that under strong THz drive, LO phonon scattering dominates both energy and momentum relaxation; that the carrier distribution maintains a heated, thermal form; and that phonon drift effects are negligible.

“DC transport in intense, in-plane terahertz electric fields in Al/sub x/Ga/sub 1-x/As heterostructures at 300 K”
Asmar NG. Markelz AG. Gwinn EG. Hopkins PF. Gossard AC.
Solid-State Electronics, vol.37, 1994, pp.693-5.
******
We report 300 K studies of the dependence of the in-plane, DC conductivity, sigma /sub DC/(E/sub omega /), of a quasi 2D electron gas on the amplitude E/sub omega / and frequency of intense, far-infrared fields (omega /2 pi =0.24-3.5 THz). We measure sigma /sub DC/(E/sub omega ///E/sub DC/), where E/sub DC/ is a small sensing field, and observe a monotonic decrease in sigma /sub DC/ with increasing E omega . Although a simple scaling ansatz collapses the measured sigma /sub DC/(E/sub omega /) data onto a single curve for frequencies from 0.25-3.45 THz (at low to moderate scaled fields), the decrease in conductivity is substantially more rapid than expected from comparison to similar data taken by Masselink et al. (Solid-St. Electron. vol.32, p.337 (1988)) at 35 GHz. We tentatively attribute this difference to effects of a high-frequency modulation in the electron temperature.

“Resonant-energy relaxation of terahertz-driven two-dimensional electron gases”
Asmar NG. Markelz AG. Gwinn EG. Cerne J. Sherwin MS. Campman KL. Hopkins PF. Gossard AC.
Physical Review B-Condensed Matter, vol.51, 1995, pp.18041-4.
******
We present experimental studies of energy loss from quasi-two-dimensional electron gases that are driven to a nonequilibrium steady state by intense, ultrahigh-frequency fields. For the Al/sub x/Ga/sub 1-x/As/GaAs heterostructures studied, longitudinal-optical (LO) phonon emission dominates energy loss across the previously unexplored frequency range from 0.2 to 3.5 THz, at moderate electron temperatures. We find an unexpected resonance in the absorbed power that is consistent with an increase near 0.5 THz in either the net LO phonon emission rate, or in the high-frequency mobility.

“Energy relaxation at THz frequencies in Al/sub x/Ga/sub 1-x/As heterostructures”
Asmar NG. Markelz AG. Gwinn EG. Hopkins PF. Gossard AC.

Semiconductor Science & Technology, vol.9, 1994, pp.828-30.
******
We report 4.2 K studies of the dependence of the in-plane, DC conductivity of a quasi 2D electron gas on the amplitude E/sub omega / of applied fields with frequencies from 0.25 THz to 3.5 THz. We analyse the dependence of sigma /sub DC/ on E/sub omega / assuming that electron-optical phonon scattering dominates energy relaxation, that the absorbed power has a Drude form and that the electron distribution is thermal. This simple analysis is self-consistent: Arrhenius plots of the estimated energy loss rate have a slope near -h omega /sub LO//k/sub 8/, for all frequencies, as expected for energy loss by optical phonon emission. We find that the effective energy relaxation time tau /sub epsilon / varies with the frequency of the applied field, from tau /sub epsilon / approximately 4 ps at 0.34 THz to tau /sub epsilon / approximately 0.3 ps at 3.45 THz.

"Far-infrared capture of electrons by DX centers"
Plombon JJ. Bewley WW. Felix CL. Sherwin MS. Hopkins P. Sundaram M. Gossard AC.
Applied Physics Letters, vol.60, no.16, 20 April 1992, pp.1972-4.
USA.
******
Intense radiation with photon energy of a few meV can induce the capture of electrons by DX centers in Al/sub x/Ga/sub 1-x/As:Si.

"Relaxation times in InAs/AlSb quantum wells"
Markelz AG. Asmar NG. Gwinn EG. Brar B.
Applied Physics Letters, vol.72, 1998, pp.2439-41.
******
We have measured energy relaxation and longitudinal-optical (LO) phonon emission times in modulation-doped InAs quantum wells driven by high dc fields, and by intense ac fields at frequencies from 0.49 to 0.6terahertz. We find that for electron temperatures between 50 and 200 K, LO phonon emission dominates energy relaxation. We determine a large net LO phonon emission time, indicating a strong LO phonon bottleneck both in high dc and in intense terahertz fields.

"Interband impact ionization by terahertz illumination of InAs heterostructures"
Markelz AG. Asmar NG. Brar B. Gwinn EG.
Applied Physics Letters, vol.69, 1996, pp.3975-7.
******
Experimental studies of InAs heterostructures illuminated by far-infrared (FIR) radiation reveal an abrupt increase in the charge density for FIR intensities above a threshold value that rises with increasing frequency. We attribute this charge density rise to interband impact ionization in a regime in which omega tau /sub m/~1, where tau /sub m/ is the momentum relaxation time, and f= omega /2 is the FIR frequency. The dependence of the density rise on the FIR field strength supports this interpretation, and gives threshold fields of 3.7-8.9 kV/cm for the frequency range 0.3-0.66 THz.

"Far-infrared saturation spectroscopy of a single square well"
Craig K. Felix CL. Heyman JN. Markelz AG. Sherwin MS. Campman KL. Hopkins PF. Gossard AC.
Semiconductor Science & Technology, vol.9, 1994, pp.627-9.
******
We have performed saturation spectroscopy measurements of the lowest intersubband transition in a single 400 AA GaAs/Al/sub 0.3/Ga/sub 0.7/As modulation-doped square quantum well. We couple intense tunable far-infrared radiation from the Santa Barbara free electron laser into our sample using an edge-coupling technique and measure absorption as a function of frequency and intensity. Saturation and frequency shifts in the absorption line are clearly observed. We attribute the frequency shifts to reductions in the many-body depolarization shift. From our preliminary measurements, we estimate the intersubband relaxation time to be 600 ps to within a factor of three.

"Temperature and intensity dependence of intersubband relaxation rates from photovoltage and absorption"
Heyman JN. Unterrainer K. Craig K. Galdrikian B. Sherwin MS.
Campman K. Hopkins PF. Gossard AC.
Physical Review Letters, vol.74, no.14, 3 April 1995, pp.2682-5. USA.
******
We report intersubband-scattering times (T/sub 1/) in a semiconductor heterostructure with intersubband spacing below the LO phonon energy. T/sub 1/ is determined by simultaneous measurements of the intersubband absorption

and the photovoltage induced by far-infrared radiation (FIR) near the intersubband transition frequency. At the lowest temperature (T=10 K) and FIR intensity (I=10 mW/cm/sup 2/), T/sub 1/=1.2+or-0.4 ns, several times longer than predicted theoretically. T/sub 1/ decreases strongly with increasing temperature and FIR intensity, to 20 ps at T=50 K in the linear regime, and to 15 ps at T=10 K and I=2 kW/cm/sup 2/.

"Optical rectification as a probe of quantum dynamics in a heterostructure"
Unterrainer K. Heyman JN. Craig K. Galdrikian B. Sherwin MS.
Superlattices & Microstructures, vol.17, 1995, pp.159-62. UK.
******
We have measured the rectification of far-infrared radiation resonant with the lowest intersubband transition of an AlGaAs/GaAs asymmetric coupled double-quantum well in which the subband spacing is 11meV. From these measurements we can extract an intersubband lifetime of 1.2+or-0.ns at low excitation intensity and T=10 K, which appears promising for devices which can operate at low excitation and temperature, such as FIR detectors or mixers. At high intensities saturation of the rectified signal is observed due to saturation of the two level system.

"Temperature of quasi-two-dimensional electron gases under steady-state terahertz drive"
Asmar NG. Cerne J. Markelz AG. Gwinn EG. Sherwin MS. Campman KL. Gossard AC.
Applied Physics Letters, vol.68, no.6, 5 Feb. 1996, pp.829-31.
Publisher: AIP, USA.
******
We use photoluminescence to study the time-average energy distribution of electrons in the presence of strong steady-state drive at terahertz (THz) frequencies, in a modulation-doped 125 AA AlGaAs/GaAs square well that is held at low lattice temperature T/sub L/. We find that the energy distribution can be characterized by an effective electron temperature, T/sub e/([right angle bracket]T/sub L/), that agrees well with values estimated from the THz-illuminated, dc conductivity. This agreement indicates that under strong THz drive, LO phonon scattering dominates both energy and momentum relaxation; that the carrier distribution maintains a heated, thermal form; and that phonon drift effects are negligible.

"Resonant-energy relaxation of terahertz-driven two-dimensional electron gases"
Asmar NG. Markelz AG. Gwinn EG. Cerne J. Sherwin MS. Campman KL. Hopkins PF. Gossard AC.
Physical Review B-Condensed Matter, vol.51, no.24, 15 June 1995, pp.18041-4.
******
We present experimental studies of energy loss from quasi-two-dimensional electron gases that are driven to a nonequilibrium steady state by intense, ultrahigh-frequency fields. For the Al/sub x/Ga/sub 1-x/As/GaAs heterostructures studied, longitudinal-optical (LO) phonon emission dominates energy loss across the previously unexplored frequency range from 0.2 to 3.5 THz, at moderate electron temperatures. We find an unexpected resonance in the absorbed power that is consistent with an increase near 0.5 THz in either the net LO phonon emission rate, or in the high-frequency mobility.

"Intersubband dynamics of asymmetric quantum wells studied by THz 'optical rectification' "
Unterrainer K. Heyman JN. Craig K. Galdrikian B. Sherwin MS. Campman K. Hopkins PF. Gossard AC.
Semiconductor Science & Technology, vol.11, 1996, pp.1591-5.
******
We have measured the rectification of far-infrared radiation resonant with the lowest intersubband transition of an AlGaAs/GaAs asymmetric coupled double-quantum well in which the subband spacing is 11 meV. From these measurements we can extract an intersubband lifetime of 1.2+or-0.ns at low excitation intensity and T=10 K, which appears promising for devices such as FIR detectors or mixers which can operate at low excitation and temperature. In order to investigate the effect of carrier concentration on the relaxation time we have performed the same experiments in a logarithmically graded quantum well.

"Nonlinear resonant optical rectification in a coupled quantum well"
Unterrainer K. Heyman JN. Craig K. Galdrikian B. Sherwin MS. Drexler H. Campman K. Hopkins PF. Gossard AC.
Surface Science, vol.361-362, 1996, pp.401-5.
******
We have measured the rectification of far-infrared radiation resonant with the lowest intersubband transition of an AlGaAs/GaAs asymmetric coupled double-quantum well in which the subband spacing is 11 meV. From these measurements we can extract an intersubband lifetime of 1.2+or-0.ns at low excitation intensity and T=10 K, which

appears promising for devices which can operate at low excitation and temperature, such as FIR detectors or mixers. From simultaneous measurements of the optical rectification and of the intersubband absorption coefficient we can determine the intensity-dependent intersubband lifetime, which shows a strong decrease for increasing intensities.

"Far-infrared pump-probe measurements of the intersubband lifetime in an AlGaAs/GaAs coupled-quantum well"
Heyman JN. Unterrainer K. Craig K. Williams J. Sherwin MS. Campman K. Hopkins PF. Gossard AC. Murdin BN. Langerak CJGM.
Applied Physics Letters, vol.68, 1996, pp.3019-21.
******
We report pump-and-probe measurements of the electron intersubband lifetime (T/sub 1/) in an AlGaAs/GaAs heterostructure using a picosecond pulsed far-infrared laser. The subband spacing (11 meV) is less than the optical-phonon energy. Time-resolved measurements yield intersubband lifetimes ranging from T/sub 1/=1.1+or-0.2 ns to T/sub 1/=0.4+or-0.1 ns depending on measurement conditions. Results are in agreement with previous lifetime measurements on the same sample using continuous excitation at intensities [left angle bracket]or=1 W/cm/sup 2/. The steady-state measurements yielded shorter lifetimes at high excitation intensities, possibly due to carrier heating leading to intersubband scattering by optical phonon emission.

"Undressing a collective intersubband excitation in a quantum well."
Craig K. Galdrikian B. Heyman JN. Markelz AG. Williams JB. Sherwin MS. Campman K. Hopkins PF. Gossard AC. Physical Review Letters, vol.76, 1996, pp.2382-5.
******
We have experimentally measured the 1-2 intersubband absorption in a single 40 nm wide modulation-doped Al/sub 0.3/Ga/sub 0.7/As/GaAs square quantum well as a function of frequency, intensity, and charge density. The low-intensity depolarization-shifted absorption occurs near 80 cm/sup -1/ (10 meV or 2.4 THz), nearly 30% higher than the intersubband spacing. At higher intensities, the absorption peak shifts to lower frequencies. Our data are in good agreement with a theory proposed by Zaluzny, which attributes the redshift to a reduction in the depolarization shift as the excited subband becomes populated.

"Intersubband scattering of cold electrons in a coupled quantum well with subband spacing below h(cross) omega /sub LO/"
Heyman JN. Barnhorst J. Unterrainer K. Williams J. Sherwin MS. Campman K. Gossard AC.
Physica E, vol.2, 1998, pp.195-9.
******
We report measurements of the intersubband scattering rate between the first and second subband in a quantum-well structure with subband spacing (11 meV) smaller than the optical phonon energy. We measure the electron population in the second subband under CW excitation by a far-infrared laser tuned to the intersubband absorption frequency. This allows us to determine the intersubband relaxation rate using detailed balance. These measurements are novel because they are performed at very low excitation densities (I[right angle bracket]or=10 mu W/cm/sup 2/). In this regime the heating of the electron gas is negligible, so that the optically excited population in the upper subband greatly exceeds any thermal population induced by laser heating. Therefore, the relaxation rate we measure is controlled by intersubband scattering rather than carrier cooling. At low temperature we obtain 0/sup -1/ W/cm/sup 2/, and approximately temperature independent for lattice temperatures between T=10 and 2.5 K.

"Saturation of THz-frequency intraband absorption in InAs/GaAs quantum dot molecules"
Boucaud P. Gill KS. Williams JB. Sherwin MS. Schoenfeld WV. Petroff PM
Applied Physics Letters, vol.77, no.4, 24 July 2000, pp.510-12.
******
We have investigated the far-infrared absorption in InAs/GaAs quantum dot molecules. The quantum dot molecules consist of two vertically coupled InAs self-assembled quantum dots separated by a GaAs barrier. The electronic coupling between the dot states results in an intraband absorption at THz frequencies. We show that this absorption can be bleached under high excitation intensity delivered by a free-electron laser. The saturation intensity is found to be on the order of 1 W cm/sup -2/. The electron relaxation time T/sub 1/ is estimated from the saturation intensity. A lower limit for T/sub 1/ of the order of 30 ps is deduced.

Terahertz Device Physics

"**Resonant Crossover of Terahertz Loss to the Gain of a Bloch Oscillating InAs/AlSb Superlattice**"
P. G. Savvidis, B. Kolasa, G. Lee, and S. J. Allen
Phys. Rev. Lett. **92**, 196802 (2004)
******
Terahertz absorption in waveguides loaded with InAs=AlSb super-superlattice mesas reveals a frequency dependent crossover from loss to gain that is related to the Stark ladder produced by an applied dc electric field. Electric field domains appear to be suppressed in the super-superlattice composed of many very short segments of superlattice, interrupted by heavily doped InAs regions. Resonant crossover is indicated by an increase in terahertz transmission as the Stark splitting or Bloch frequency determined by the applied dc electric field exceeds the measurement frequency.

"Theoretical electromagnetic analysis of a grating-gated double quantum well FET terahertz detector".
Popov VV. Polischuk OV. Teperik TV. Horing NJM. Peralta XG. Allen SJ. Wanke MC.
IEEE-NANO 2003 Proceedings (Cat. No.03TH8700). IEEE. Part vol.2, 2003, pp.224-7 vol.2.
******
We analyze resonant behavior in terahertz absorption, in connection with resonant photoconductance recently observe in field effect transistors with a double-quantum-well channel (DQW-FET). This phenomenon is potentially important for fast, tunable, terahertz detectors. Important features are the several sharp photoconductance resonances that tune with grating gate voltage and the fact that the multiple resonance response grows and narrows at elevated temperatures becoming more pronounced as temperature increases up to 40 K. Our electrodynamic analysis of the THz absorption spectrum compared to the experimental data establishes that the resonance is determined by standing plasma waves in the DQW channel, with multiple-resonances corresponding to spatial harmonics of standing plasmons under the metallic grating gate. This is due to static spatial modulation of the electron density in the channel induced by the gate. Higher order plasmon modes become more optically active as! the depth of the DQW density modulation approaches unity. We find the maximum potential absorbance, at plasma resonance, to be 50%. Moreover, the strongest absorption also occurs when the standing plasmon resonance coincides with the fundamental dipole mode of the ungated portion of the channel.

"THz detection by resonant 2-D plasmons in field effect devices",
Peralta XG. Allen SJ. Wanke MC. Harff NE. Lilly MP. Simmons JA. Reno JL. Burke PJ. Eisenstein JP. Knap W. Deng Y. Rumyantsev S. Lu J-Q. Shur MS.
International Journal of High Speed Electronics, vol.12, no.3, Sept. 2002, pp.925-37.
******
We demonstrate resonant detection of terahertz radiation by two-dimensional plasma waves in two field effect devices: a commercial field effect transistor (FET) and a double quantum well field effect transistor with a periodic grating gate. In both devices, the standing 2-D plasmon is tuned to the frequency of the THz radiation by varying the gate bias. The double quantum well field effect transistors exhibits a rich photoconductive response corresponding to spatial harmonics of the standing 2-D plasmons under the metal part of the periodic gate.

"Absorption of terahertz radiation by plasmon modes in a grid-gated double-quantum-well field-effect transistor." Popov VV. Polischuk OV. Teperik TV. Peralta XG. Allen SJ. Horing NJM. Wanke MC.
Journal of Applied Physics, vol.94, no.5, 1 Sept. 2003, pp.3556-62.
******
The terahertz absorption spectrum of plasmon modes in a grid-gated double-quantum-well (DQW) field-effect transistor structure is analyzed theoretically and numerically using a first principles electromagnetic approach and is shown to faithfully reproduce important physical features of recent experimental observations. We find that the essential character of the response-multiple resonances corresponding to spatial harmonics of standing plasmons under the metal grating-is caused by the static spatial modulation of electron density in the channel. Higher order plasmon modes become more optically active as the depth of the electron density modulation in the DQW tends towards unity. The maximum absorbance, at plasma resonance, is shown to be 1/2. Furthermore, the strongest absorption also occurs when the standing plasmon resonance coincides with the fundamental dipole mode of the ungated portion of the channel.

"Terahertz dynamics in semiconductor quantum structures"
Allen SJ.
Conference Digest. Twenty Seventh International Conference on Infrared

and Millimeter Waves (Cat. No.02EX561). IEEE. 2002, pp.Pl1-2.
******
Summary form only given. The Terahertz part of the electromagnetic spectrum defines a gap in solid state technology. This is most apparent if one focuses on sources. In this presentation we review experiments with the UCSB free-electron laser that have revealed the rich phenomena related to photon assisted transport in semiconductor quantum transport devices and the use of quasi-optical arrays and waveguide structures to measure Terahertz admittance of electrically biased devices.

"Terahertz photoconductivity and plasmon modes in double-quantum-well field-effect transistors"
Peralta XG. Allen SJ. Wanke MC. Harff NE. Simmons JA. Lilly MP. Reno JL. Burke PJ. Eisenstein JP.
Source
Applied Physics Letters, vol.81, no.9, 26 Aug. 2002, pp.1627-9.
******
Double-quantum-well field-effect transistors with a grating gate exhibit a sharply resonant, voltage tuned terahertz photoconductivity. The voltage tuned resonance is determined by the plasma oscillations of the composite structure. The resonant photoconductivity requires a double-quantum well but the mechanism whereby plasma oscillations produce changes in device conductance is not understood. The phenomenon is potentially important for fast, tunable terahertz detectors.

"Simulations of electric field domain suppression in a superlattice oscillator device using a distributed circuit model."
Daniel ES. Gilbert BK. Scott JS. Allen SJ.
IEEE Transactions on Electron Devices, vol.50, no.12, Dec. 2003, pp.2434-44.
******
We present a method for simulating static domain formation in distributed negative differential resistance devices using a distributed circuit array model coupled with quantum transport simulations. This simulation method is applied to the case of a superlattice Bloch oscillator to ascertain the efficacy of electric field domain wall suppression by micro shunt side walls. Two independent simulation mechanisms using the same basic distributed circuit model are employed to separate simulation artifacts from true physical trends. Simulations are presented, suggesting that the presence of the micro shunt can suppress domain formation above a critical device bias voltage. The simulated dependence of this critical voltage on macroscopic device parameters is presented.

"Two-dimensional terahertz photonic crystals fabricated by deep reactive ion etching in Si."
Jukam N. Sherwin MS.
Applied Physics Letters, vol.83, no.1, 7 July 2003, pp.21-3.
******
Two-dimensional terahertz photonic crystals were manufactured from Si using deep reactive ion etching. Arrays of square holes with widths of 80 (100) mu m and lattice constants of 100 (125) mu m were etched through 500- mu m-thick wafers with high resistivity. Stop bands with transmittance [left angle bracket]1% and widths [right angle bracket]200 GHz were observed near 1 THz for light with an electric field vector in the plane of the wafers (TE polarization).

"A terahertz grid frequency doubler."
Moussessian A. Wanke MC. Yongjun Li. Jung-Chih Chiao. Hegmann FA. Allen SJ. Crowe TW. Rutledge DB.
International Microwave Symposium Digest (Cat. No.97CH36037). IEEE. Part vol.2, 1997, pp.683-6 vol.2.
******
We present a 144-element terahertz quasi-optical grid frequency doubler. The grid is a planar structure with bow-tie antennas as a unit cell each loaded with a planar Schottky diode. The grid has an output power of 5.5 mW at 1 THz for 3.1- mu s, 500-GHz input pulses with a peak power of 36 W. This is the largest recorded output power for a multiplier at terahertz frequencies.

"Possible THz gain in superlattices at a stable operation point."
Wacker A. Allen SJ. Scott JS. Wanke MC. Jauho A-P.
Physica Status Solidi B-Basic Research, vol.204, 1997, pp.95-7.
******
We demonstrate that semiconductor superlattices may provide gain at THz frequencies at an operation point which is stable against fluctuations at lower frequency. While an explicit experimental demonstration for the sample

considered could not be achieved, the underlying principle of quantum response is quite general and may prove successful for differently designed superlattices.

"Terahertz dynamics in quantum structures: towards a fundamental terahertz oscillator"
Allen SJ. Scott JS. Wanke MC. Maranowski K. Gossard AC. Rodwell MJW. Chow DH.
Terahertz Sources and Systems. Proceedings of the NATO Advanced Research Workshop. Kluwer Academic. 2001, pp.3-14. Dordrecht, Netherlands.
******
The terahertz part of the electromagnetic spectrum marks a decade wide gap in semiconductor technology between transport-based electronics and quantum transition based photonics. As such, it appears that potential, future solid-state oscillators, that will fill this gap, will marry transport and quantum transitions in semiconductor quantum structures. Fundamental limits of quantum transport devices like resonant tunneling diodes are discussed. Monolithic power combining leads naturally to multi-quantum well superlattices in uniform electric fields, which are recognized as Bloch oscillators. Multi-quantum well superlattices are integrated into quasi-optical arrays and loaded into terahertz cavities driven by radiation from the UCSB free-electron lasers in order to measure the change in terahertz dynamical conductance under electrical bias.

"Open confocal resonators with quasi-optical arrays to measure THz dynamics of quantum tunneling devices."
Scott JS. Wanke MC. Allen SJ. Maranowski KD. Gossard AC. Chow DH.
Proceedings of SPIE, vol.3617, 1999, pp.176-80.
******
A semi-confocal etalon has been sued as a quasi-optical cavity to explore the dynamical conductance of Bloch-oscillating superlattices at terahertz frequencies. To maintain both DC and irradiated field uniformity and to maximize the coverage of the cavity mode with the devices of interest, the tunneling structures have been photolithographically fabricated into micro-sized mesa-isolated devices forming a quasi-optical square array interconnected by a metal grid with a period which is less than the wavelength in the semiconductor of the IR probe radiation. At a given bias on the device array and scanning the cavity through a resonance, the loss and reactance of the tunneling devices embedded in the array is measured by detecting a change in the position and line shape of the cavity resonance.

"Terahertz response of an InGaAs/AlAs resonant tunnelling diode"
Scott JS. Kaminski JP. Allen SJ. Chow D. Lui M. Liu TY.
Semiconductor Science & Technology, vol.9, 1994, pp.530-2.
******
We have measured the broad-band terahertz response of a state-of-the-art InGaAs/AlAs resonant tunnelling diode from 120 GHz to 3.9 THz using the free-electron lasers at the University of California, Santa Barbara. A tungsten whisker antenna in a conventional probe station is used to couple the far-infrared radiation into the device. By normalizing the rectified response in the resonant tunnelling regime with the off-resonant response we are able to remove the antenna frequency effects and the frequency dependence controlled by the much slower RC time constant and measure the relaxation time due to the quantum inductance.

"Terahertz response of resonant tunneling diodes."
Scott JS. Kaminski JP. Allen SJ. Chow DH. Lui M. Liu TY.
Surface Science, vol.305, 1994, pp.389-92.
******
We have measured the broad-band terahertz response of state of the art InGaAs/AlAs and InAs/AlSb resonant tunneling diodes from 180 GHz to 3.THz using the free-electron lasers at UCSB. A tungsten whisker antenna in a conventional probe station is used to couple the far-infrared radiation into the device. Normalizing the resonant tunneling response with the off-resonant response allows us to circumvent the much slower RC time constant of the device and consequently enables a measurement of the relaxation time due to the quantum inductance.

"Terahertz frequency response of an In/sub 0.53/Ga/sub 0.47/As/AlAs resonant-tunneling diode"
Scott JS. Kaminski JP. Wanke M. Allen SJ. Chow DH. Lui M. Liu TY.
Applied Physics Letters, vol.64, 1994, pp.1995-7.
******
We have measured the room-temperature, broad-band, terahertz response of a high-speed In/sub 0.53/Ga/sub 0.47/As/AlAs resonant-tunneling diode from 120 GHz to 3.9 THz using the free-electron lasers at UCSB. The

“rectified” response is measured with a conventional probe station by using the tungsten probe tip as a whisker antenna. Normalizing the rectified response in the resonant-tunneling regime with the off-resonant response we remove the extrinsic frequency dependence controlled by the antenna and the RC time constant and measure an intrinsic relaxation time.

“A concept for a tunable antenna-coupled intersubband terahertz (TACIT) detector”
Cates CL. Briceno G. Sherwin MS. Maranowski KD. Campman K. Gossard AC.
Physica E, vol.2, 1998, pp.463-7.
******
Detectors based on intersubband transitions in quantum wells have great potential for use between one and several terahertz. We propose a tunable, antenna-coupled, intersubband terahertz (TACIT) detector that is both sensitive and fast, with a speed limited only by the intersubband relaxation rate (1 ns at T=10 K, [left angle bracket]or=10 ps at T=50 K). The detector is sensitive over a narrow range of frequencies, and the frequency of peak absorption can be tuned by applying a bias voltage to the device.

“Photoelectrochemical etching of high aspect ratio submillimeter waveguide filters from n/sup +/ GaAs wafers”
Khare R. Hu EL. Reynolds D. Allen SJ.
Applied Physics Letters, vol.61, 1992, pp.2890-2.
******
A 200 mu m high-pass filter has been fabricated using the photoelectrochemical (PEC) etch process to form a series of waveguides through a Si-doped n/sup +/ GaAs (1*10/sup 18/ cm/sup -3/) substrate. A metal mask on the sample surface with 100 mu m square openings and 41 mu m spaces was used to locally prevent PEC etching. The sample was etched in a (4:1:50) HCl:HNO/sub 3/:H/sub 2/O electrolyte for 1.5 h using an argon ion laser (514 nm) at an intensity of 0.7 W/cm/sup 2/, and an applied bias of 0.35 V. The result was a series of highly anisotropic waveguides with a (3:1) aspect ratio. The transmittance curve had a cutoff of 45 cm/sup -1/ and a transmittance of 20% just above the cutoff.

“Two-dimensional terahertz photonic crystals fabricated by deep reactive ion etching in Si”
Jukam N. Sherwin MS.
Applied Physics Letters, vol.83, 2003, pp.21-3.
******
Two-dimensional terahertz photonic crystals were manufactured from Si using deep reactive ion etching. Arrays of square holes with widths of 8(100) mu m and lattice constants of 100 (125) mu m were etched through 500- mu m-thick wafers with high resistivity. Stop bands with transmittance [left angle bracket]1% and widths [right angle bracket]20GHz were observed near 1 THz for light with an electric field vector in the plane of the wafers (TE polarization). The observed stop bands are close to TE photonic band gaps predicted by a two-dimensional calculation.

Terahertz Free-electron Laser Instrumentaion

“First lasing of the UCSB 30 mu m free-electron laser.”
Ramian G. Kaminski J. Allen SJ.
Nuclear Instruments & Methods in Physics Research Section
A-Accelerators Spectrometers Detectors & Associated Equipment, vol.393,
1997, pp.220-4.
******
Third harmonic lasing has been achieved in a free-electron laser specifically designed to operate in that mode. So far, 40 W at 41 mu m wavelength and 5.16 MeV beam energy has been measured. One of the most difficult challenges has been suppression of lasing at the fundamental wavelength. This is currently achieved with an intracavity cesium iodide reststrahlen filter, but eventually, the original grating design will be needed to provide full tunability. Operation of this FEL demands electron beam stability and control system accuracy at the limits of the present system. Further progress in the development of this FEL may require significant improvement in these areas.

“Characterization of photoconducting materials using variable length picosecond terahertz pulses”
Cole B. Hegmann F. Williams J. Sherwin M. Beeman J. Haller E.
Proceedings of Spie - the International Society for Optical Engineering, vol.3617, 1999, pp.164-73.
******

A source of high-intensity, ultra-short terahertz pulses has been developed. The operation and performance of a terahertz pulse-slicing system for use with the UCSB free-electron lasers are discussed. Short pulses are sliced from the microsecond long output of the free-electron laser using laser-activated semiconductor switches; the pulse length may be freely varied from a few picoseconds up to four nanoseconds. The temporal response of a heavily compensated gallium-doped germanium photoconductor has been investigated. At low excitation intensity, a recombination time of 2+or-0.1 ns is found. At higher THz pulse powers non-exponential relaxation is observed; the data is well modeled using a rate equation approach and including impact-ionization effects due to the terahertz-heated free holes.

"Generation of picosecond far-infrared pulses using laser activated semiconductor reflection switches"
Hegmann FA. Sherwin MS.
Proceedings of SPIE, vol.2842, 1996, pp.90-105.
******
A source of high-intensity, picosecond-to-nanosecond far-infrared pulses has been developed at the UCSB Center for Free-Electron Laser Studies. The microsecond-long, far-infrared output of the UCSB free-electron laser is sliced into shorter pulses using laser-activated semiconductor reflection switches. We have observed pulse durations as short as 20 ps at 22 cm/sup -1/. An overview of the design and performance of the pulse-slicer system is given.

"Time-resolved photoresponse of a gallium-doped germanium photoconductor using a variable pulse-width terahertz source".
Hegmann FA. Williams JB. Cole B. Sherwin MS. Beeman JW. Haller EE.
Applied Physics Letters, vol.76, no.3, 17 Jan. 2000, pp.262-4.
******
Picosecond to nanosecond-wide terahertz pulses are used to study the fast photoresponse of a gallium-doped germanium (Ge:Ga) photoconductor operating at 4.2 K. A recombination time of about 2 ns is observed in the time-resolved photoresponse. Laser-activated semiconductor reflection switches are used to "slice" the variable-width terahertz pulses from the quasicontinuous-wave output of a free-electron laser.

Reviews

"Materials science in the far-IR with electrostatic based FELs."
Allen SJ. Craig K. Galdrikian B. Heyman JN. Kaminski JP. Scott JS. Sherwin MS. Unterrainer K. Wanke M. Campman K. Hopkins PF. Gossard AC. Chow DH. Lui M. Liu TK.
Nuclear Instruments & Methods in Physics Research Section A-Accelerators
Spectrometers Detectors & Associated Equipment, vol.358, 1995, pp.536-9.
******
A technology gap exists between approximately 100 GHz and approximately 10 THz. Free-electron lasers (FELs), driven by high quality, relatively low energy electron beams from electrostatic accelerators, and capable of generating kilowatts of coherent, tunable radiation, are ideally suited to explore the enabling science for future technology in this spectral range. We describe two experiments that use terahertz "optical rectification" to measure (i) the intensity and temperature dependent energy relaxation in quantum wells and (ii) the intrinsic relaxation of resonant tunneling diodes. Both benefit from the power and tunability of the UCSB FELs.

"Terahertz dynamics in semiconductor quantum structures."
Allen SJ.
Conference Digest. Twenty Seventh International Conference on Infrared
and Millimeter Waves IEEE. 2002, pp.Pl1-2.
******
"The Terahertz part of the electromagnetic spectrum defines a gap in solid state technology. This is most apparent if one focuses on sources. In this presentation we review experiments with the UCSB free-electron laser that have revealed the rich phenomena related to photon assisted transport in semiconductor quantum transport devices and the use of quasi-optical arrays and waveguide structures to measure Terahertz admittance of electrically biased devices.

"Probing tetrahertz dynamics in semiconductor nanostructures with the UCSB free-electron lasers"
Allen SJ. Craig K. Felix CL. Guimaraes P. Heyman JN. Kaminski JP. Keay BJ. Markelz AG. Ramian G. Scott JS. Sherwin MS. Campman KL. Hopkins PF. Gossard AC. Chow D. Lui M. Liu TY.
Journal of Luminescence, vol.60-61, 1994, pp.250-5.

******

The UCSB free-electron lasers provide kilowatts of continuously tunable radiation from 120 GHz to 4.8 THz. They have the most impact on terahertz science and technology that require a tunable, high power source to explore nonlinear dynamics or that sacrifice incident power to recover the linear response of systems with very small cross-section. We describe three experiments that demonstrate the utility of these lasers in experiments on the terahertz dynamics of semiconductor nanostructures: (i) terahertz dynamics of resonant tunneling diodes; (ii) saturation spectroscopy of quantum wells and (iii) photon-assisted tunneling in superlattices.

"Materials science in the far-IR with electrostatic based FELs"
Allen SJ. Craig K. Galdrikian B. Heyman JN. Kaminski JP. Scott JS. Sherwin MS. Unterrainer K. Wanke M. Campman K. Hopkins PF. Gossard AC. Chow DH. Lui M. Liu TK.
Nuclear Instruments & Methods in Physics Research Section A-Accelerators Spectrometers Detectors & Associated Equipment, vol.358, no.1-3, 1995, pp.536-9.
******

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“Probing tetrahertz dynamics in semiconductor nanostructures with the UCSB free-electron lasers”
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“Probing terahertz electron dynamics in semiconductor nanostructures with the UC Santa Barbara FELs.
Kaminski JP. Allen SJ. Sherwin M. Keay B. Scott JS. Craig K. Heyman J. Guimaraes P. Campman KL. Hopkins PF. Gossard AC. Chow D. Lui M. Liu TY.
Nuclear Instruments & Methods in Physics Research Section A-Accelerators
Spectrometers Detectors & Associated Equipment, vol.341, no.1-3, 1994, pp.169-73.
******

The UCSB free electron lasers radiate quasi CW tunable radiation from 120 GHz to 4.8 THz at the kilowatt power level. These lasers enable researchers to probe high frequency nonlinear electron transport in state-of-the-art semiconductor nanostructures. The impact of this research could have important consequences in the fields of high frequency semiconductor science and technology. Three experiments are described that demonstrate the application of FELs in exploring terahertz dynamics of semiconductor nanostructures: (i) photon-assisted tunneling in a semiconductor superlattice; (ii) dynamical response of a resonant tunneling diode; and (iii) saturation spectroscopy of a single square quantum well.