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13. ABSTRACT (Maximum 200 words)

This research explored the conceptual, theoretical, and practical aspects of controlling quantum electron transport in nanometer-scale solid-state electronic structures and devices. In this context, control is envisioned to include compositional design of the materials, as well as the influence of tailored external laser fields. Experiments were carried out indicating that solid-state structures may be generated to control quantum electron scattering processes. In addition, theoretical research was carried out exploring the principles involved, including the prospect of spatial and temporal control of electron wave packet motion. For that purpose, concepts from optimal control theory were utilized, as well as a special closed loop learning control algorithms. These quantum electron transport control techniques exhibit good quality robustness to environmental noise.

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I. STATEMENT OF PROBLEM STUDIED.

As solid-state electronic devices become smaller, they will inherently run into the limit where quantum electron transport phenomena become dominant. It remains an open question as to whether operations in this regime have special technical advantages over traditional classically operating devices. The fundamental process in electron transport is scattering, and the objective of this research was to ascertain the degree to which coherent electron scattering in semiconductors could be manipulated and controlled. The key operating principle is the manipulation of electron quantum wave interferences by means of (a) the design of special solid-state structures, (b) the introduction of bias voltages, and (c) the use of ultrafast tailored external laser fields. The research demonstrated the basic feasibility of playing on quantum wave interference to manipulate coherent electron scattering. The richest pay-off will come from operating in two dimensions with temporal control. A summary of the experimental and theoretical findings of the research is given below.

II. SUMMARY OF RESULTS.

(1) Observations of Magnetic Focusing in Two-dimensional Hole Systems[1].
This work resulted in the reporting of the first observation of transverse magnetic hole focusing in high quality two-dimensional hole systems confined in square and triangular quantum wells grown on (311)A GaAs substrates. The results demonstrated ballistic hole transport over distances up to 11 microns, and allowed the probing ov constant energy contours in k-space for these two types of confinement.

(2) Ultrafast Carrier-Carrier Scattering Among Photoexcited Nonequilibrium Carriers in GaAs[2].
This research involved the study of carrier-carrier scattering in photoexcited electron-hole plasmas in GaAs, at plasma densities from 10^{15} to 10^{17} cm^{-3}, using numerical solution of the dynamically screened Boltzmann equation and classical molecular dynamics. The solution of the dynamically screened Boltzmann equation indicated that for excited electrons, scattering among the injected carriers was as important a scattering process as LO-phonon emission at densities greater than about 8×10^{15} cm^{-3}, and at 10^{17} cm^{-3}, the photoexcited electrons were nearly thermalized in 150 fsec. As a result of weaker screening, the interaction between carriers had a stronger effect in this case than when a low density of energetic electrons was immersed in a cool background plasma, where previous work had shown that carrier-carrier scattering became as significant as LO-phonon emission at a density of about 8×10^{16} cm^{-3}. It was also found that classical molecular-dynamics calculations were dominated by nonphysical effects at shorter times, arising from the point-like nature of the simulated carriers.

(3) Novel surface gate structure to induce sharp potential barriers in tow-dimentsional electron systems[3].
In this research, a novel surface gate structure, consisting of a central gate and two side gates, was proposed to generate an effectively sharp potential barrier for two dimensional electrons confined to a semiconductor heterojunction deep below the sample surface. The side gates were biased at a higher potential than the central gate, to enhance the large-wave-vector Fourier components of the potential and therefore, to compensate partially for the strong decay, due to fringing fields, of these components, as a function of the distance below the surface. The reflection coefficient calculated for the proposed potential barrier exhibited strong oscillations as a function of barrier height, much stronger than a conventional single gate. The results suggested that the proposed gate structure should find use in realization of an electron interferometer which can serve as a building block for novel electron interference devices.

(4) Surface resonant tunneling transistor: A new negative transconductance device[4]
This work involved a new three-terminal device, the surface resonant tunneling transitor, which was realized by the molecular beam epitaxial cleaved edge overgrowth technique in the GaAs/AlGaAs system. The device exhibited negative transconductance, as well as negative differential resistance. Some possibilities for future applications of the device to low-power logic circuits were also explored.

(5) Tranverse magnetic focusing and the dispersion of GaAs 2D holes at (311)A heterojunctions[5].
This research involved transverse magnetic focusing experiments on two-dimensional hole systems confined in square and triangular quantum wells grown on (311)A GaAs substrates. The focusing barriers were oriented along different crystallographic directions and allowed the derivation of the constant energy contours in k-space. The results indicated a nearly elliptical shape for these contours, which were interpreted in light of a lateral surface superlattice induced by corrugations at the heterojunction.

(6) Quantum reflection and transmission of ballistic two-dimensional electrons by a potential barrier[6].
In this research, measurements of the reflection and transmission coefficients of ballistic two dimensional electrons by a potential barrier, induced via a surface gate, revealed that both coefficients vary gradually with the barrier height when it is less than the electron Fermi energy. Superimposed on the gradual variation, oscillatory structure which was consistent with interference resonances were also observed. The data implied that the potential barrier seen by the two-dimensional electrons was sharp, compared to the electron wavelength.

(7) The effect of control field and measurement imprecision on laboratory feedback control of quantum systems[7].

This research was based on recent theoretical studies which had suggested the feasibility of laboratory adaptive feedback optimal control (AFOC) of chemical processes with the use of ultrashort laser pulses. The feedback process was introduced to provide robustness to laboratory error and electric field design uncertainties. Adaptive approaches for laboratory applications were also explored. To foster laboratory implementation, a number of questions still needed to be answered. The research addressed the problem of AFOC in the presence of laboratory errors and uncertainties, both in adjusting the control parameters, and in measuring the results. Through simulations, it was shown that optimization methods exist which are robust against systematic errors, and certain optimization methods were also fairly robust against uncertainties. These results suggested that the effect of inevitable laboratory errors could be overcome. Furthermore, the results suggested that noise is not a major problem, and optimization in the laboratory is feasible.

(8) Optimally designed potentials for control of electron-wave scattering in semiconductor nanodevices[8].
This research examined control of plane-wave scattering using designed potential structures in solid-state devices with dimensions of the electron coherence length. Reflection coefficients at specified incident electron energies were controlled by exploiting the quantum interferenc effects associated with the wavelike nature of the electrons, through optimally designed manipulation of the solid-generated scattering potential. This work was motivated by the increasing ability to fabricate semiconductor structures with controlled layer thickness and lateral features, and here, the goal was to demonstrate the degree of coherent electron control achievable through the employment of optimal design tools. The case where the potential form was restricted to a fixed number of rectangular barriers was examined. Here, the optimization of the design was performed with respect to the barrier width and spacings, in order to achieve the desired reflection coefficients at one or more incident energies. The case where the potential was not restricted to any particular form was also examined, and here, optimal control theory was employed to optimize the scattering potential form in order to achieve the desired reflection coefficients over a range of incident electron energies. The possibility of extending this work to controlling electron wave-packet structures was also examined.

(9) Ballistic transport in the upper subband of a two-dimensional electron system[9].
In this work, the observation of ballistic transport of upper subband electrons in a two-dimensional electron system (2DES) confined to a square quantum well with two occupied electrical subbands was reported. Two types of experiments were performed. In the first type, a specially designed transverse magnetic focusing device was used. In this device, the usual reflecting barrier was replaced by a surface-gate-induced, tunable potential barrier to selectively reflect and magnetically focus the upper subband electrons. In the second type of experiment, a surface-gate-induced periodic potential was created in a double-subband-occupied 2DES and the nagnetoresistance along the modulation direction was measured. Fourier analysis was used to separate the commensurability oscillations originating from ballistic electrons of different subbands.

(10) Observation of ballistic transport in upper subband of a two-dimensional electron system[10].
This work involved a specially designed transverse magnetic focusing experiment on a two-dimensional electron system confined to a square quantum well with two electric subbands occupied. The reflecting barrier of a usual magnetic focusing device was replaced by a surface-gate-induced, tunable potential barrier that allowed selective reflection and magnetically focused the upper subband electrons while the lower subband electrons passed over the barrier and were not focused. The focusing of the upper subband electrons was observed. The weakness of the focusing signal for the upper subband ballistic electrons suggested that they have a surprisingly short ballistic mean free path compared to the lower subband electrons.

(11) Relation between quantum computing and quantum controllability[11].
This work demonstrated that the universality of any quantum computing element can be understood and verified via a precise mathematical criterion which tests for the controllability of an associated quantum control system. This relation between quantum computing and quantum control was deeper, in that tools of coherent control of quantum dynamics may be used to arrive at specific designs for quantum computing devices.

(12) Learning Control of Quantum Mechanical Systems by Laboratory identification of Effective Input-Output Maps[12].
This work addressed a new algorithm for laboratory learning control of quantum mechanical systems. The learning control was achieved through the laboratory identification of a successive number of effective input-output maps for the quantum mechanical system. The input to these maps consisted of a linearly independent set of control fields, and the output consisted of the resultant observations in the laboratory. In this research, the observations were taken as the temporal evolution of the target expectation value. From this information, an effective input-output map was produced, and the best control to meet a desired objective was then identified within the domain of the map. The process may be repeated as desired, if higher quality control is necessary. The basic logic behind this laboratory learning-based approach was presented, along with a simulated illustration of its behavior for a simple few-state control problem.

(13) The Effect of Quantum Dispersion on Laboratory Feedback Optimal Control[13].
The effect of quantum dispersion (i.e., a multitude of quantum states corresponding to each value of an observable) on laboratory feedback optimal control was studied. It was shown by numerical and analytical means that including the variance of the observable in the objective functional, as well as the presence of modest noise in the controls, can steer the system into a low-variance quantum state, or if possible, an eigenstate of the observable.

(14) Configurational Disorder and the Local Field Effects in Nonlinear Optical Systems[14].
In this work, we argued that in nonlinear optical systems with atoms randomly distributed in crystals or amorphous hosts, one should go beyond the Clausius-Mossoti limit in order to take into account the effect of local field fluctuations induced by configurational disorder in atom position. This effect was analyzed by means of a random local mean field approach with neglect of correlations between dipole moments of different atoms. The formalism was applied to three-level Lambda-type systems with quantum coherence possessing an absorptionless index of refraction and lasing without inversion. We showed that the effect of configurational fluctuations resulted in the suppression of the atom susceptibility compared with the predictions based on the Clausius-Mossoti equation.

(15) Optimal Control of Laser-Induced Transient Birefringence in Liquid Crystals[15].
In this work, optimal control theory was applied to design a laser pulse to produce an anisotropic change of the refraction index in the vicinity of the isotropic-nematic phase transition in liquid crystals. The laser-induced birefringence originated from the orientational anisotropy induced by the laser field, that is enhanced significantly due to the excluded volume effect. The shape of the optimal pulse was analyzed for different values of relaxation time and different molecule concentrations.

(16) Ramifications of Feedback for Control of Quantum Dynamics[16].
Generalized feedback techniques are operative both in the theoretical design of quantum controls, as well as ultimately, in their laboratory implementation. This work surveys the nature of these feedback loops and their significance. Ultimately, such feedback in the laboratory may also be turned around to learn about structural dynamical features of the quantum system.

(17) A Phenomenology of Relaxor Ferroelectrics[17].
This research proposed a phenomenological theory for the dielectric properties of relaxor ferroelectrics, based on the assumption that the polar clusters distributed in a highly polarizable host lattice is responsible for the relaxor behavior. Two major differences between relaxor ferroelectrics and conventional order-disorder ferroelectrics were employed for the theory: (i) the existence of the broad distribution of local fields experienced by each polar cluster, and (ii) the existence of the distribution of relaxation times giving rise to non-exponential non-critical kinetics which may complete with the critical slowing down near the ferroelectric phase transition. We numerically illustrated predictions of the theory for the dielectric response for relaxors with incipient ferroelectric order, like PMN or (x < 0.022), and for relaxors undergoing true first order ferroelectric phase transitions like PST or PLZT.

(18) Dispersion-free Wave Packets and Feedback Solitonic Motion in Controlled Quantum Dynamics[18].
This research considered the feasibility of creating dispersion-free solitary quantum-mechanical wave packets. The analysis was carried out within a general framework of quantum optimal control theory. A key to the realization of solitary quantum wave packets was the ability to create travelling wave potentials U(x - vt) with coordinated space and time dependence where v is a characteristic speed. As an illustration, the case of an atom translating in a designed optical trap was considered. Three examples were treated within this framework: (A) the motion of a dispersion-free travelling bound state, (B) feedback-stabilized solitonic motion, and (C) feedback-stabilized solitonic motion in the presence of auxiliary physical objectives. The quantum solitons of (B) and (C) satisfied the Schrödinger-type equation with laboratory feedback in the form of an observation of the probability density. This feedback was essential for maintaining the solitonic-type motion. Some generalizations and potential applications of these concepts were also looked at.

(19) Reduced Control Dynamics for Complex Quantum Systems[19].
In this work, a reduced dimensional control dynamics formulation was presented for an arbitrary number of degrees of freedom. The traditional control feedback partial differential equation then became a small set of ordinary differential equations amenable to efficient numerical solution. This approach was capable of finding optimal solutions with only a few feedback iterations, thereby dramatically reducing the effort to obtain control designs. As an example, the reduced formalism was applied to selective dissociation of triatomic molecules.

(20) Nonstationary Optimal Paths and Tails of Prehistory Probability Density in Multistable Stochastic Systems[20].
The tails of prehistory probability density in nonlinear multistable stochastic systems driven by white Gaussian noise were analyzed by employing the concepts of nonstationary optimal fluctuations. Results of numerical simulations showed that the prehistory probability density was non-Gaussian and highly asymmetrical, and that it was an essential feature of noise-driven fluctuations in nonlinear systems. We also showed that, in systems with detailed balance, the prehistory probability density was the conventional transition probability the obeys the backward Kolmogorov equation.

(21) Ballistic Transport in a Two-Subband Two-Dimensional Electron System[21].
This research was a quantitative study of ballistic transport, via measurements of commensurability oscillations (CO's) in a two-dimensional electron systems confined to a wide square quantum well with two electric subbands occupied. The Fourier power spectrum of the CO's showed two clear-frequency components that corresponded to ballistic transport in the upper and lower subbands. Through inverse Fourier transformation of each individual frequency component, we reconstructed the CO's of ballistic electrons in different subbands and extracted their scattering times.

(22) Tunable spin-splitting and spin-resolved ballistic transport in GaAs/AlGaAs two-dimensional holes[22].
This work reported quantitative experimental and theoretical results revealing the tunability of spin-splitting in high-mobility GaAs two-dimensional hole systems, confined to either a square or a triangular quantum well, via the application of a surface-gate bias. The spin-splitting depended on both the hole density and the symmetry of the confinement potential, and was largest for the highest densities in asymmetric potentials. In the triangular well, when the spin-splitting was sufficiently large, the measured commensurability oscillations induced by a one-dimensional periodic potential exhibited two frequencies, providing clear evidence for spin-resolved ballistic transport.

III. Bibliography and list of all publications and technical reports supported by this grant.

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V. Report of inventions (by title only). None