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Semiconductor nanostructures and photonic crystal microcavities for quantum information processing at terahertz frequencies

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The overall goal of this research is to explore the feasibility of a novel scheme for all-optical quantum information processing using new types of semiconductor nanostructures and electromagnetic microcavities which resonate in the rapidly-developing terahertz frequency range. Our highly-integrated research program is also pushing back the frontiers of terahertz science and technology.

The research program is divided into four tasks.

1. The design, fabrication and characterization of two-dimensional photonic crystal resonators (PCRs)[2] and surface-plasmon-based[3] resonators for *terahertz* frequencies.
2. The fabrication and characterization of a new kind of self-assembled semiconductor nanostructure, the quantum post. When doped with a single electron, the quantum post is designed to resonate at terahertz frequencies. The ground and first excited states will serve as |0> and |1> of a quantum bit.
3. The use of a non-destructive optical readout[4] to measure the quantum state, energy relaxation, and decoherence in naturally-occurring model semiconductor quantum bits – the ground and first excited states of electrons bound to shallow impurities in GaAs.
4. The integration of quantum bits into resonators to demonstrate strong coupling between qubits and resonators.

We report on progress for the first three tasks, which are running in parallel.

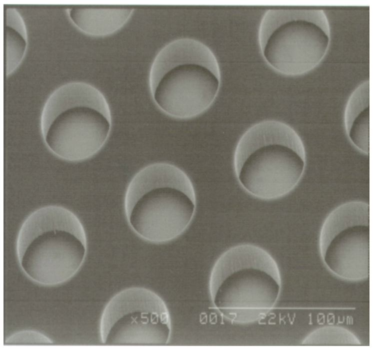

Fig. 1: SEM of terahertz Si photonic crystal slab 48 μm thick. Lattice constant a=64 μm, hole radius r=0.30 a.

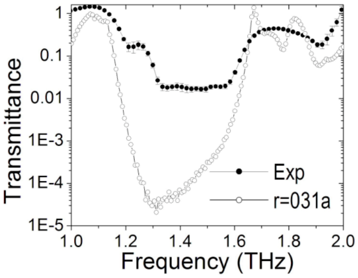

Fig. 2: Experimental and computed transmittance spectra of a photonic crystal slab. (Yee and Sherwin, unpublished)

1. Two-dimensional photonic crystals for terahertz frequencies: Photonic crystals are structures in which the index of refraction is modulated periodically. Photonic crystals are the subject of intense study and development at optical and telecommunications wavelengths. To a large extent, designs developed for telecommunications wavelengths can be simply scaled up in size by about 200 to operate at 1 THz. Fabrication becomes more accurate because of relatively large features. A scanning electron micrograph (SEM) of a thin Si photonic crystal slab (PCS) is shown in Fig. 1.

Characterization is the real challenge at terahertz frequencies. Experimental measurements of transmittance through the edge of the PCS, measured using a fourier transform spectrometer, are shown in Fig. 2. The measured transmittance drops to less than 10%, between 1.2 and 1.6 THz. Finite-difference time-domain computations, also shown in Fig. 2, show good agreement with the onset of the band gap. The high-frequency end of the gap is extremely sensitive to the diameter of the holes, and fits well for a hole diameter of 0.31 times the lattice

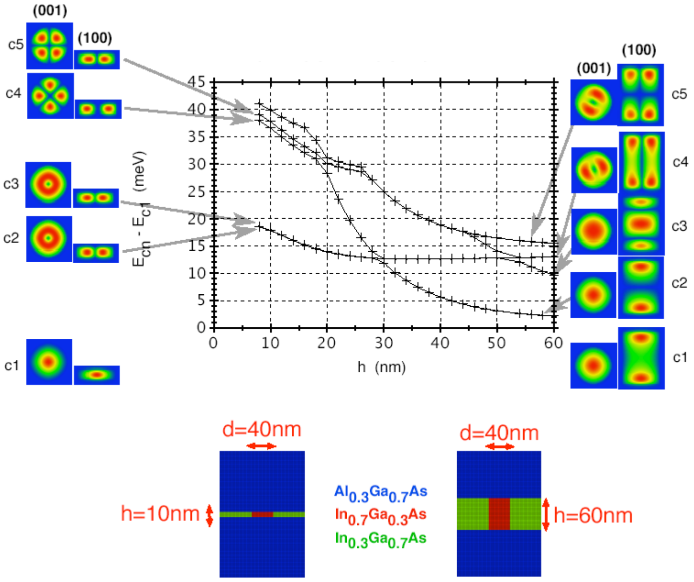

Fig. 3: Graph: Computed energies of electronic states of quantum posts referenced to energy of ground state, as the post height is varied up to 60 nm. Bottom: schematic diagram of quantum posts. Sides: probability density associated with electronic wave functions in planes bisecting the round posts through the center horizontally (left) and vertically (right). (C. Pryor, unpublished).

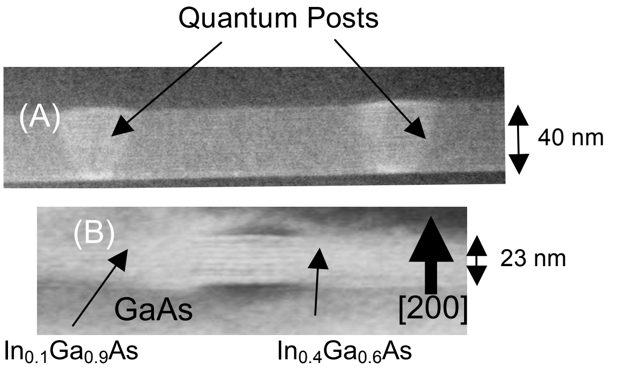

Fig. 4: Cross-sectional transmission electron micrographs of self-assembled InGaAs quantum posts. (Jun He, P. Petroff, et. al., unpublished)

constant (3% bigger than nominal). The minimum computed transmission for this structure, which consists of only 5 rows of holes, is much lower than the 1% measured experimentally. We attribute this discrepancy to leakage around the slab in the experiment.

Design, fabrication and testing of photonic crystal waveguides and resonators is under way.

2. *Self-assembled nanostructures for terahertz applications:* Self-assembled InAs quantum dots grown on GaAs have been studied intensively for more than a decade. The lowest-frequency transition for a doped self-assembled quantum dot is typically around 40 meV (10 THz), near the optical phonon energy and hence highly susceptible to decoherence via electron-phonon coupling. At frequencies well below 10 THz, coupling with optical phonons is quenched and coupling with acoustic phonons is extremely weak. In order to reduce the intraband transition frequency to the 1-3 terahertz frequency range in a controlled fashion and with large oscillator strength, we have begun growing, characterizing and modeling "quantum posts." As shown in the theoretical predictions (state-of-the art k.p calculations, including effects of strain) of Fig. 3, the lowest-energy transition of a doped quantum post 40 nm high is expected to be about 5 meV (1.25 THz). In the MBE growth process, a layer of self-assembled InAs quantum dots, grown by MBE, nucleates the growth of quantum posts. Subsequent to the first layer of dots, thin layers of InAs are alternated with GaAs, with long growth interruptions to allow extensive intermixing of In and Ga. The strain field drives the In to migrate preferentially to the positions of the seed QDs. By repeating the alternation of InAs and GaAs, one builds up a post-shaped region which is In-rich, and hence confines electrons and holes. Cross-sectional transmission electron micrographs (TEMs) of quantum posts 23 and 40 nm tall are shown in Fig. 4. Quantum posts are being characterized by scanning x-ray photoelectron spectroscopy to determine atomic concentration profiles, interband spectroscopy (ensemble and single quantum dot), terahertz spectroscopy, and capacitance-voltage spectroscopy. Detailed comparisons with theory are being made. The long-term plan is to use the two lowest electronic states of quantum posts as |0> and |1> of a qubit, and to test their energy relaxation and decoherence times.

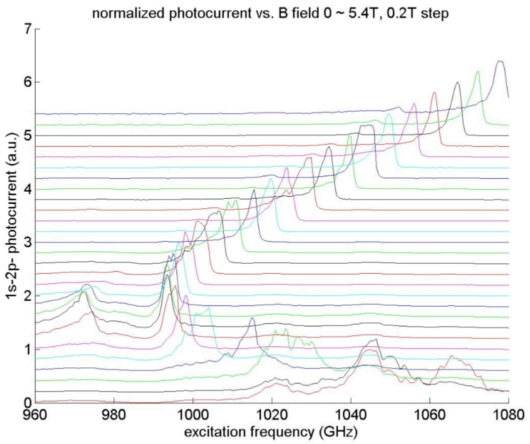

Fig. 5: Terahertz photocurrent spectroscopy of the $1s$-$2p^-$ transition of Hydrogenic donors in GaAs (0.2 GHz resolution). The source, custom made by Virginia Diodes, Inc, reaches these very high frequencies by multiplying the output of a microwave synthesizer by 72.

3. Hydrogenic impurities in GaAs as model semiconductor quantum bits. Impurities and defects in semiconductors are under consideration as potential quantum bits in a variety of physical systems. Electrons bound to shallow donors in GaAs (for example, Si substituting for Ga) are a promising candidate as a model qubit for quantum information processing using terahertz frequencies. Fig. 5 shows a series of spectra in which the photocurrent is plotted as a function of excitation frequency at magnetic fields up to 6 T. At zero magnetic field, three peaks are visible, which we attribute to three different species of donors. As the magnetic field is increased, a single peak begins to dominate and narrows dramatically. This is the lowest orbital transition of the dominant hydrogenic donor, the 1s-2p (m=-1) transition. The spectrum here is for a large *ensemble* of donors, and we believe the peak to be inhomogeneously broadened—but nevertheless has only 3 GHz FWHM at 5 T (0.3%, or 13 μeV). We have developed a novel, non-destructive optical read-out of the population of the ground state of donors in GaAs [4]. We will use this method to measure energy relaxation (T_1) and decoherence (T_2) times. We also plan to incorporate shallow donors into photonic crystal resonators to search for vacuum Rabi splittings.

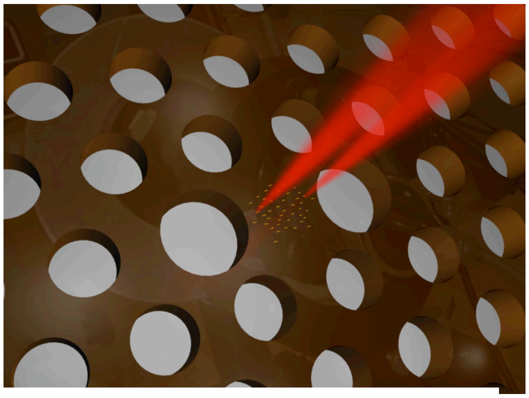

Fig. 6: Schematic diagram of all-optical quantum information processor.

In the long term, we are guided by the vision of an all-optical quantum information processor, shown schematically in Fig. 6, in which quantum bits can be individually tuned in and out of the strong coupling condition with the resonator in which they are embedded via the optical Stark effect induced by focused near-ir lasers, and can also be read out by the same lasers. Along the way, we are pushing the state of the art of terahertz science and technology and our understanding of the fundamental interactions of quantum-confined electrons in semiconductors.

References

[1] For further information about this project email **sherwin@physics.ucsb.edu** or link to http://www.iqcd.ucsb.edu/sherwingroup/
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