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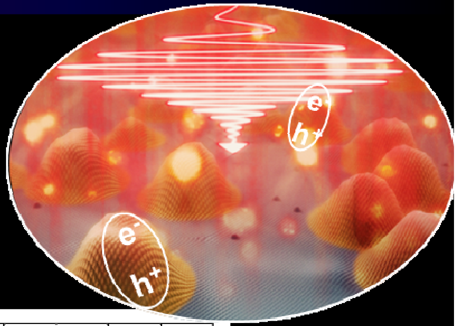
- Omics group has organised 500 conferences, workshops and national symposium across the major cities including SanFrancisco,Omaha,Orlado,Rayleigh,SantaClara,Chicago,Philadelphia,Unitedkingdom,Baltimore,SanAntanio,Dubai,Hyderabad,Bangaluru and Mumbai.

Ultrafast Adiabatic Rapid Passage in a Single Semiconductor Quantum Dot

Kimberley C. Hall
Dalhousie University, Nova Scotia, Canada



Outline

Introduction

- *Semiconductor Qubits in InAs quantum dots*
- *Ultrafast optical quantum gates*

Adiabatic Rapid Passage on Excitons

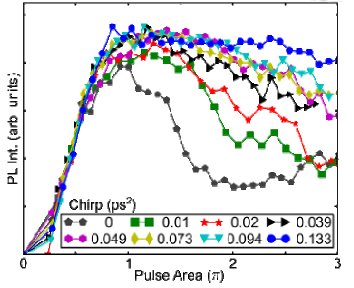
- *Linear pulse chirp leads to a robust single qubit π gate*

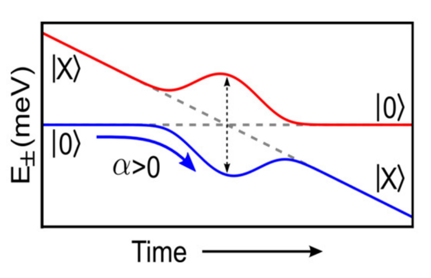
Infrared Quantum Control Experiments

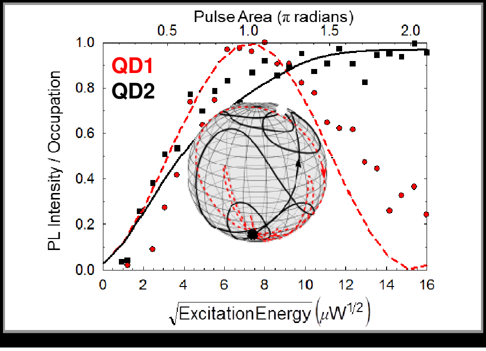
- *InAs/GaAs, MicroPL, Exciton Qubits*

Results: *New regime of strong, rapidly varying Rabi energy*

- *20 x reduction in gate time*
- *Chirp sign dependence: phonon-mediated dephasing suppressed for positive chirp at 10 K*







Dalhousie University
Ultrafast Quantum Control Group

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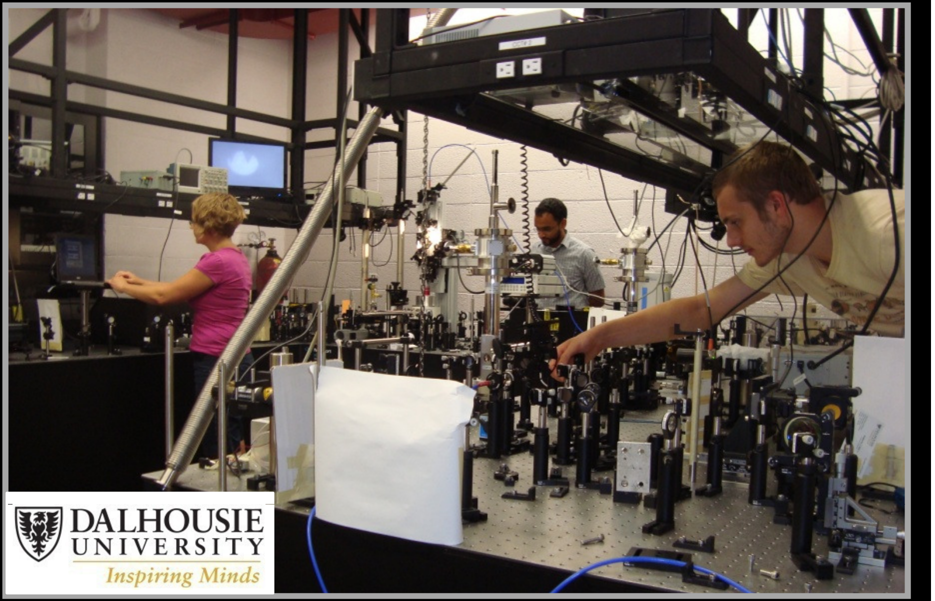
Angela Gamouras (PhD, grad.)
Daniel Webber (PhD)
Ajan Ramachandran (PhD)
Mathew Britton (Undergrad.)
Eric Dilcher (Undergrad.)
Luke Hacquebard (Undergrad.)
Kimberley Hall (Director)



University of Central Florida
Semiconductor Laser Group

Sabine Freisem (Senior Res. Scientist)
Dennis Deppe (Director)

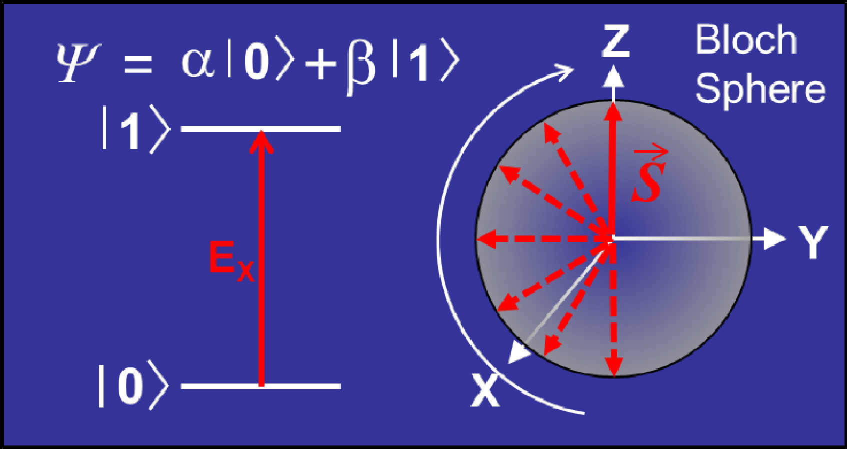
Solid State Qubits: Semiconductor Quantum Dots

Semiconductor solid state qubits:

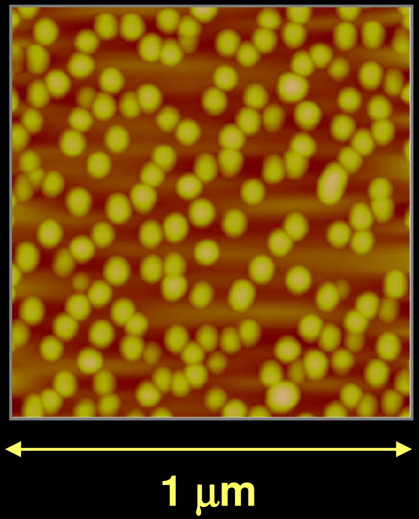
- *Processing, Photonic technology*
- *Interfacing with classical computers*

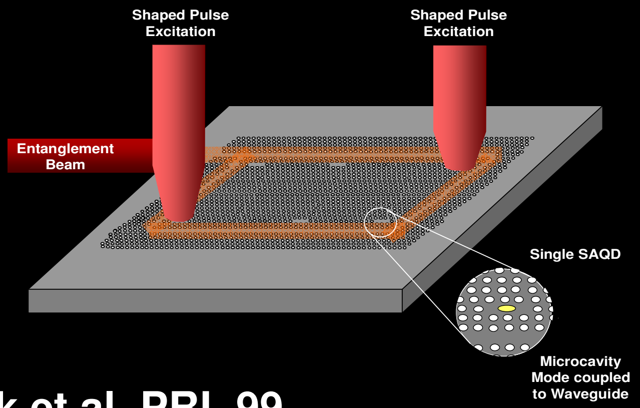
Short optical pulses:

- *Fast gates relative to T2*
  (Dynamical decoupling, Quant. Error Corr.)
- *Pulse shaping, Parallel processing (CIQC)*



InAs/GaAs
Self-assembled QDs

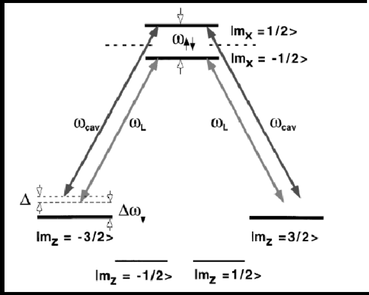


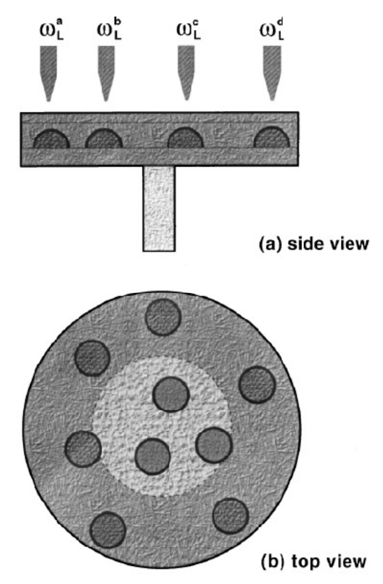


Clark et al. PRL 99, 040501 (2007).

Troiani et al.
PRB 62, R2263 (2000).

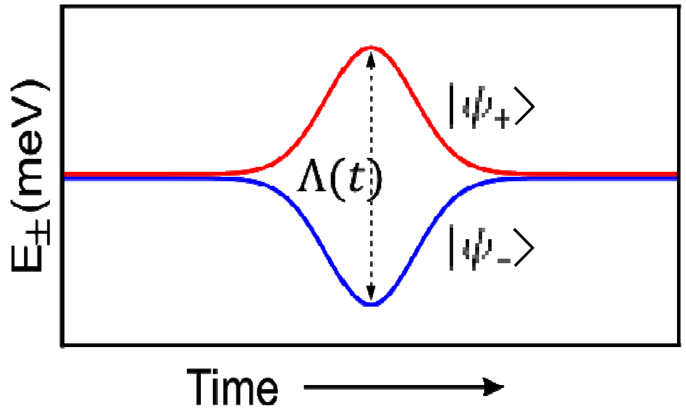
Imamoglu et al.
PRL 83, 4204 (1999).





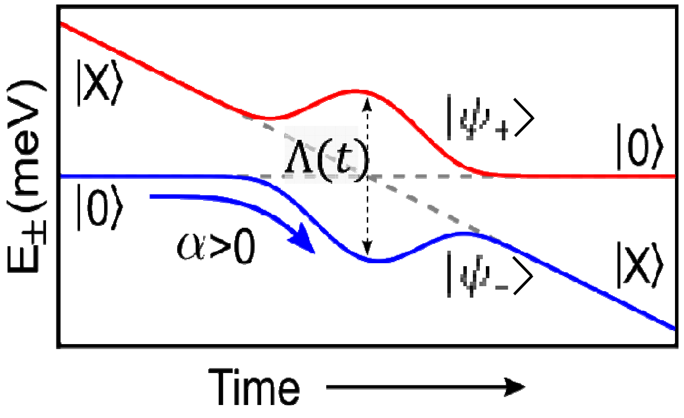
Single Qubit π Gate via Adiabatic Rapid Passage

Rabi Rotations:



$$E(t) = E_n(t)e^{-i\omega_0 t}$$

Adiabatic Rapid Passage:



$$E(t) = E_p(t)e^{-i(\omega_0 t+\alpha t^2)}$$

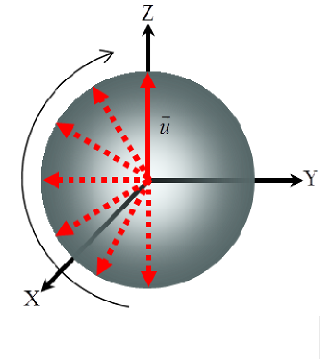
Dressed states in Light Field:

$|\psi_+\rangle, |\psi_-\rangle$

$$E_\pm = \pm\frac{1}{2}\Lambda(t)$$

$$= \pm\frac{1}{2}\sqrt{\Omega(t)^2 + \Delta(t)^2}$$

Rabi Frequency **Detuning**

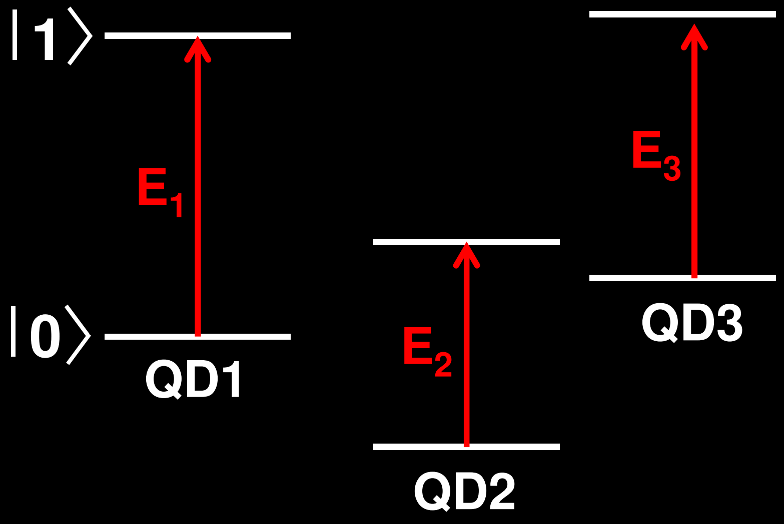


$$\theta(t) = \left(\frac{\mu}{\hbar}\right)\int_{-\infty}^{\infty} E_0(t)dt$$

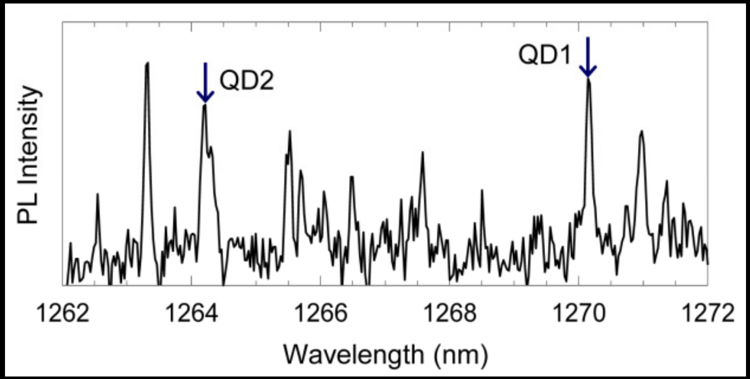
- In Rabi rotations, the pulse is resonant with exciton transition at all times (constant phase, Δ=0), and the Bloch vector undergoes a pure rotation about a single axis.
- In ARP, a *chirped* laser pulse is used for qubit control: $\omega(t) = \omega_X + \alpha t$
  - *System remains in eigenstate of "QD+Light" system*
  - *The Bloch vector follows the Light torque vector adiabatically*
  - *"QD+Light" system evolves through an anti-crossing, resulting in inversion of the qubit*

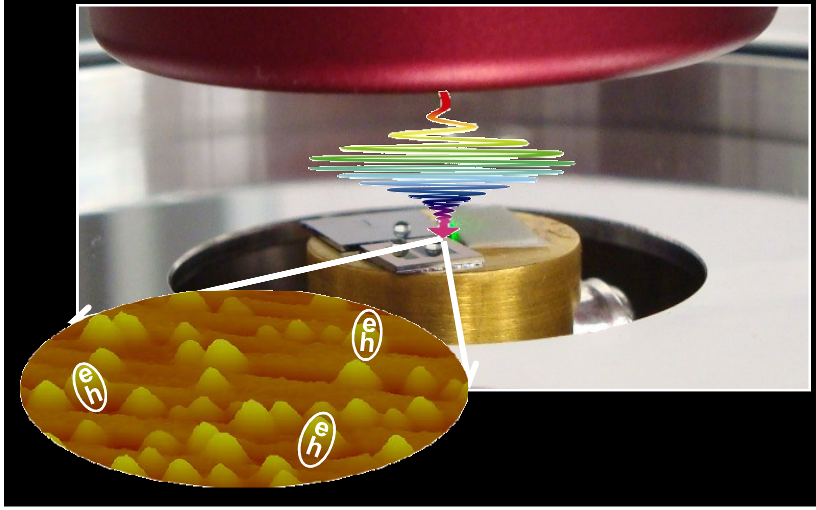
Parallel Single Qubit Gate on Distant Quantum Dots

- Excitons in different quantum dots can have different dipole moments and transition energies: *Distinguishable Qubits*



<u>Proof of Principle</u> demonstration of simultaneous deterministic control:
QD1: 2π gate; QD2: π gate





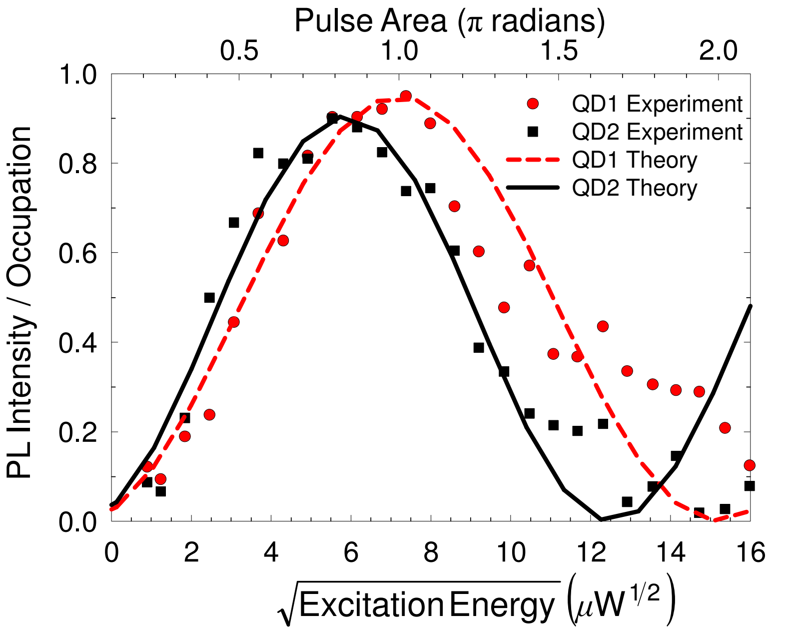
Parallel quantum processing

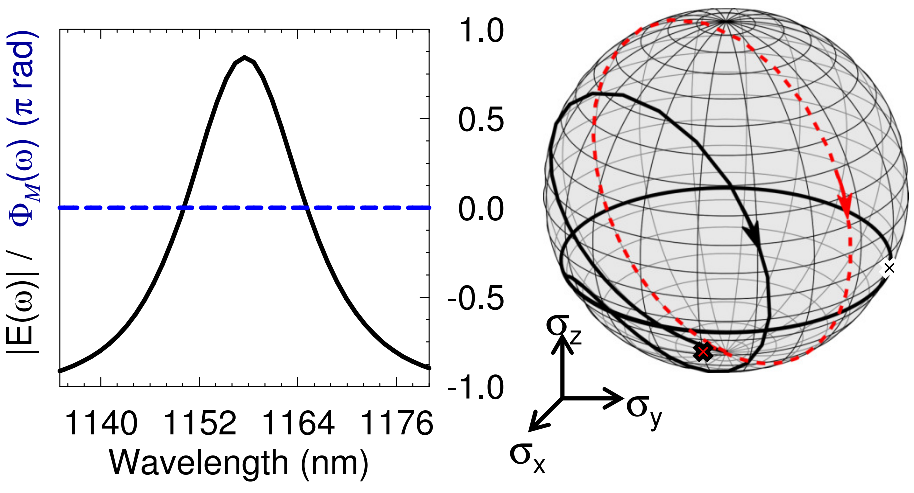
Could encode problem-specific, <u>complex instruction sets</u> in pulse shape

Sanders, PRA 59, 1098 (1999).
Amitay Chem. Phys. Lett. 359, 8 (2002).

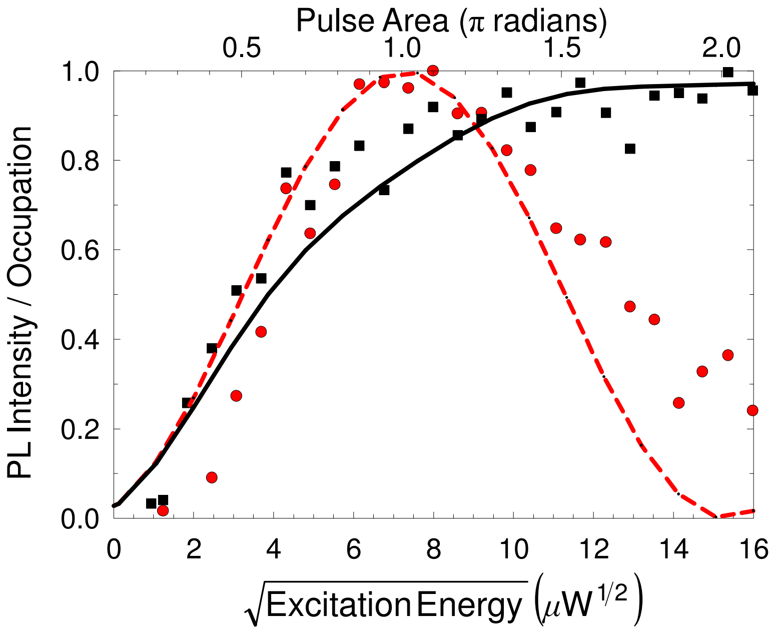
Application of Optimal Quantum Control to Simultaneous π, 2π Gates in Two Different QDs

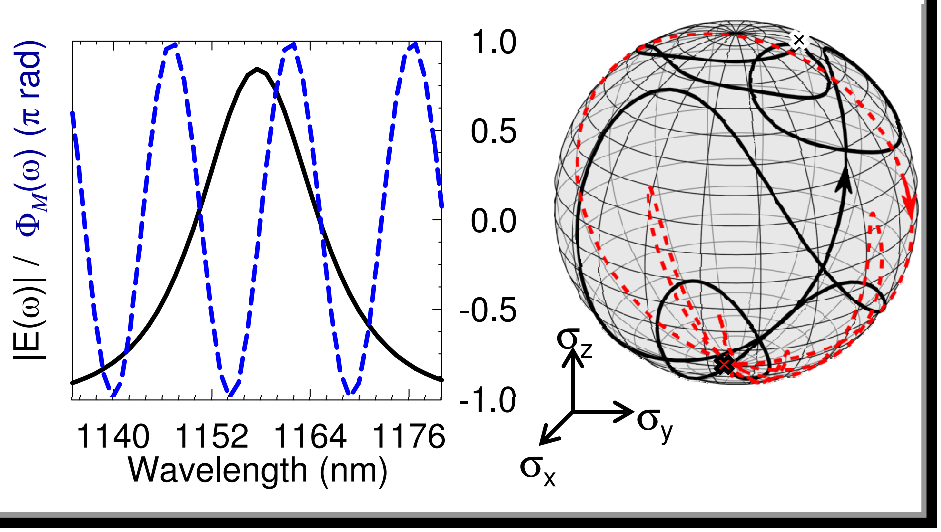
Unshaped (TL) Pulse





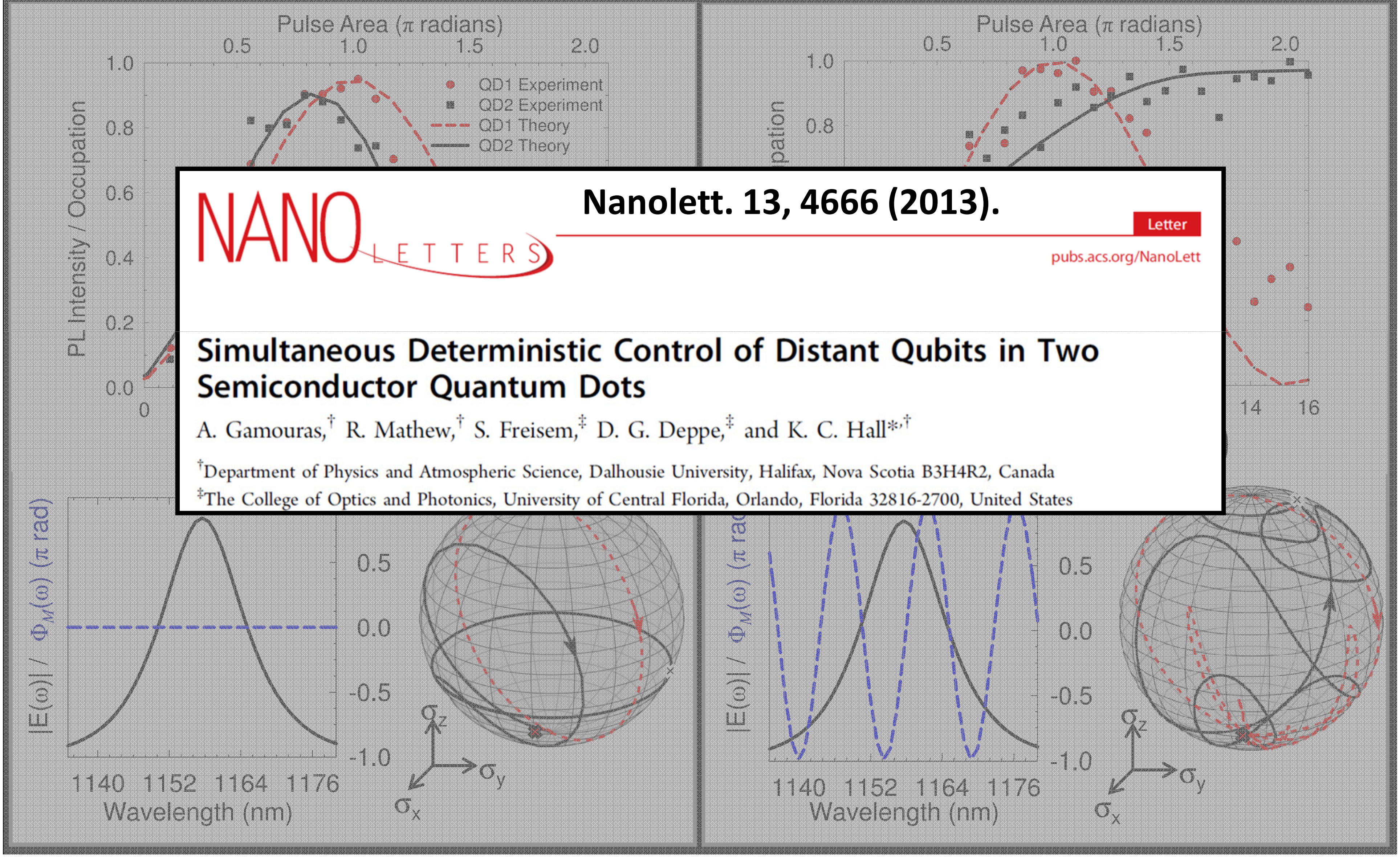
Optimum Shaped Pulse





Application of Optimal Quantum Control to Simultaneous π, 2π Gates in Two Different QDs

Unshaped (TL) Pulse **Optimum Shaped Pulse**



Nanolett. 13, 4666 (2013).

NANO LETTERS
Letter
pubs.acs.org/NanoLett

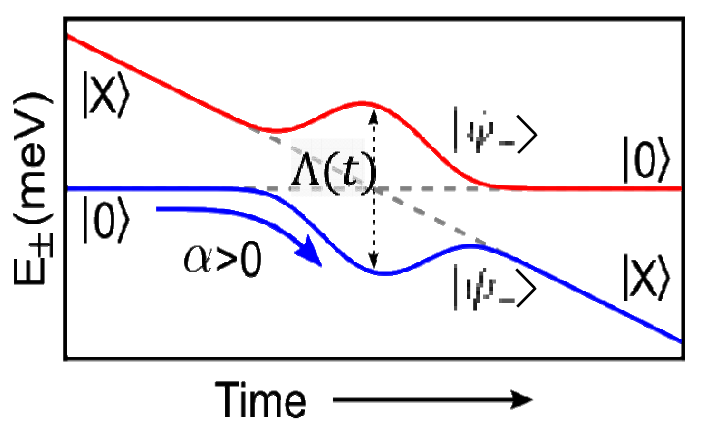
Simultaneous Deterministic Control of Distant Qubits in Two Semiconductor Quantum Dots

A. Gamouras,[†] R. Mathew,[†] S. Freisem,[‡] D. G. Deppe,[‡] and K. C. Hall*[,†]

[†]Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia B3H4R2, Canada
[‡]The College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816-2700, United States

Single Qubit π Gate via Adiabatic Rapid Passage

Adiabatic Rapid Passage:



$$E(t) = E_p(t)e^{-i(\omega_0 t+\alpha t^2)}$$

- The advantage of ARP is that, unlike Rabi rotations, it is robust against variations in the experimental parameters:
  - *Uncertainties in QD Parameters:* $\hbar\omega_i, \vec{\mu}_{i,j}$
  - *Fluctuations in Laser Power, Wavelength*

- This robustness makes ARP attractive for a variety of applications:

Quantum Computing

Bose-Einstein Condensate in semiconductor

Single and entangled photon sources

All-optical switching

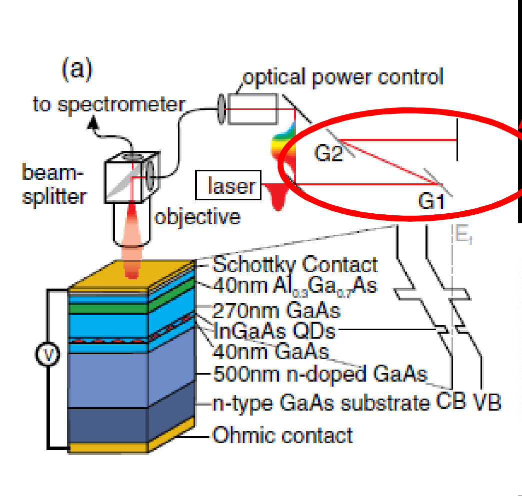
- A robust π gate is especially attractive for reducing decoherence via *dynamical decoupling*:
  - *Viola and Lloyd, PRA 58, 2733 (1998).*
  - *Axt et al., PRB 71, 155305 (2005).*
  - *Hodgson et al., PRB 78, 165311 (2008).*

Single Qubit π Gate via Adiabatic Rapid Passage

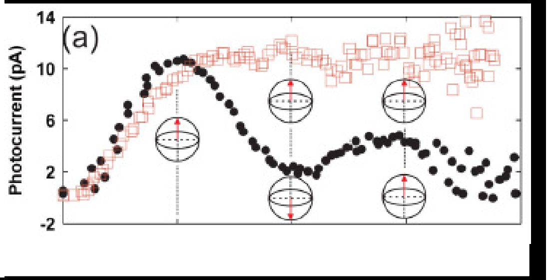
- ARP in a single semiconductor QD was recently demonstrated experimentally, with *long control pulses*:15-40 ps

  Wu *et al.*
  PRL 106, 067401 (2011).

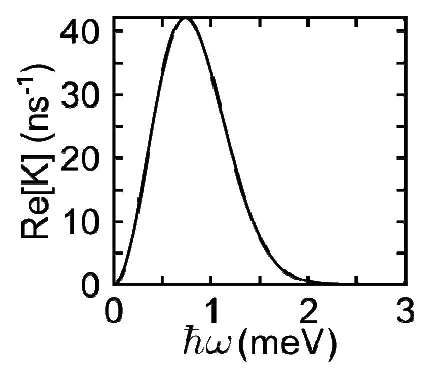
  Simon *et al.*
  PRL 106, 166801 (2011).



Grating stretcher:
- constant $\underline{\Phi''(\omega)}$



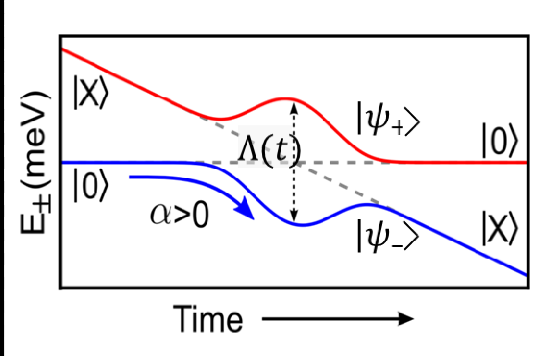
- Shorter gate pulses would permit *more operations within the decoherence time* AND may enable one to *engineer the strength of coupling to phonons*



K: Response function electron-phonon coupling

- Resonant coupling to LA phonons is dominant decoherence mechanism during control pulse
  $\longrightarrow \mathrm{Re}[K(\hbar\Lambda)]$

- Short pulses enables large $\hbar\Lambda$ and/or use of pulse sequences to achieve dynamical decoupling



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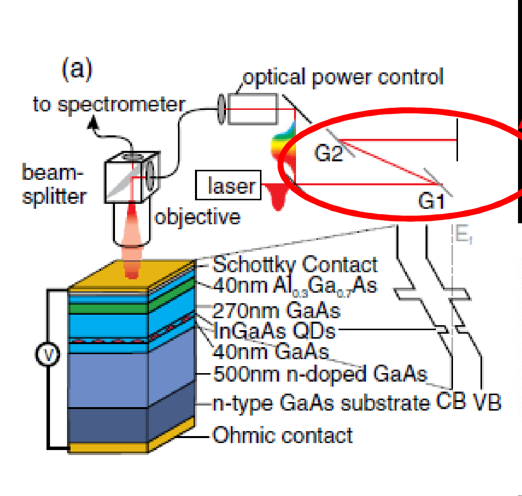

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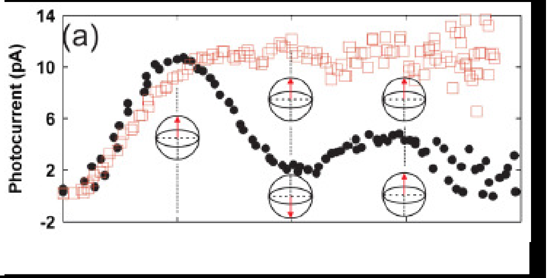

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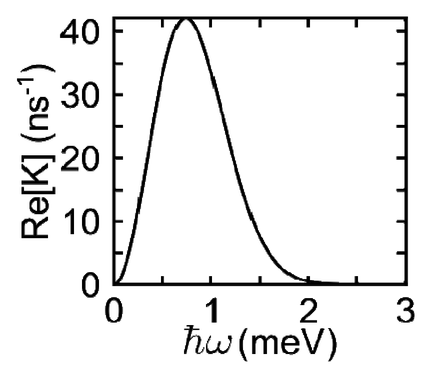

Mathew *et al.*
in progress (2014).

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$$\longrightarrow \mathrm{Re}[K(\hbar\Lambda)]$$

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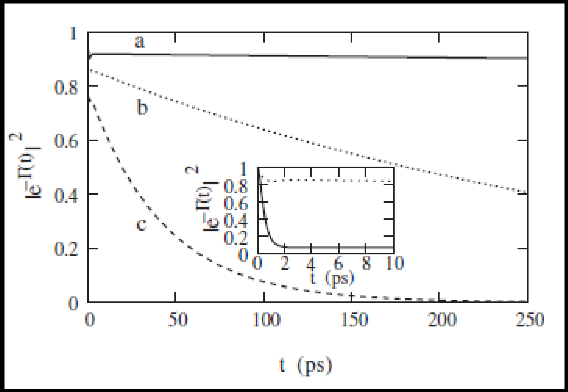
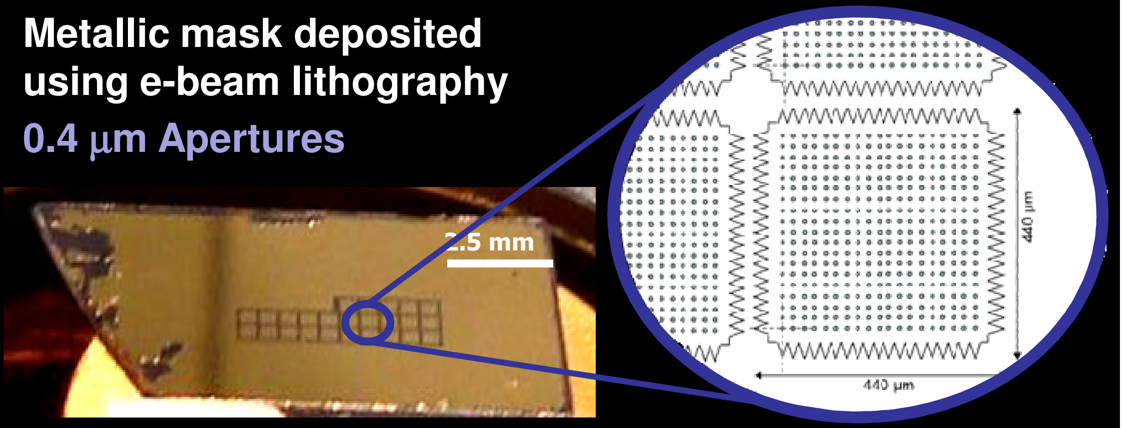


Hodgson *et al.*
PRB 78, 165311 (2008).

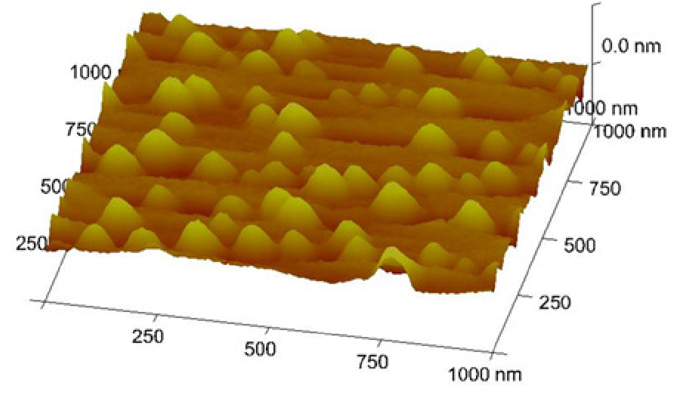
Self-Assembled Quantum Dot Samples for Infrared Quantum Control

Metallic mask deposited using e-beam lithography

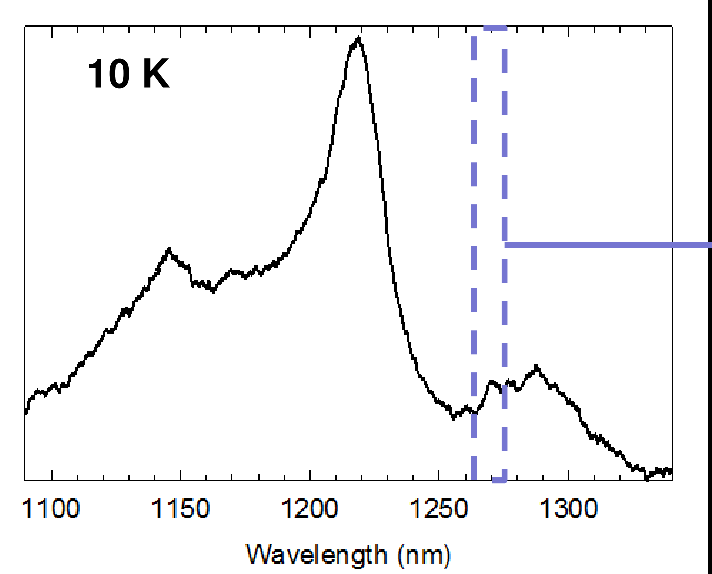
0.4 µm Apertures



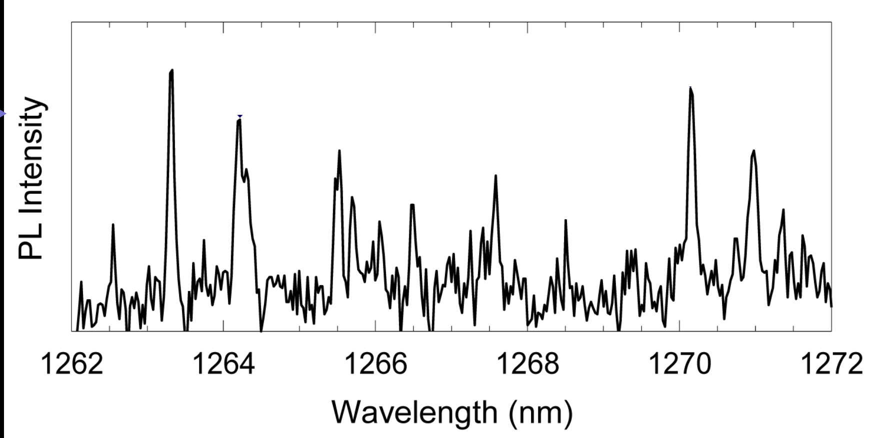
Avg. Height: 9 nm; Diameter: 20 nm



- Quantum dots are characterized using µ-PL and PLE and have a bimodal size distribution. Select QDs with transition energies near 1.3µm for OQC

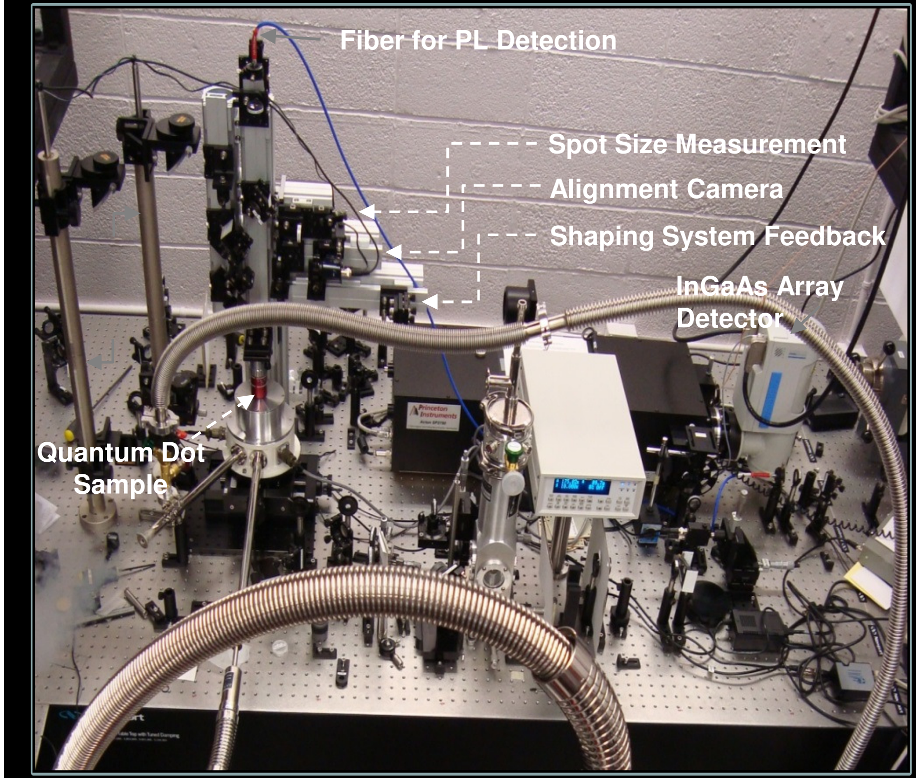


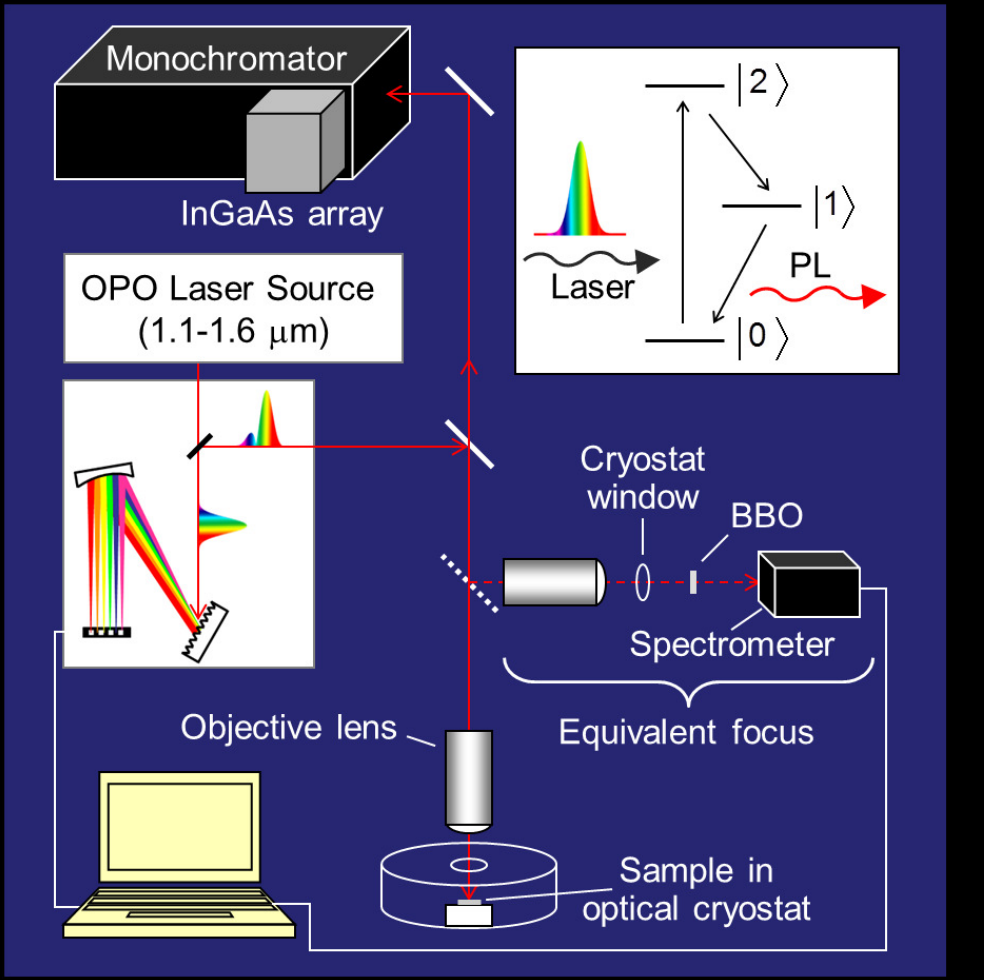
1×10^{10} cm^{-2} (1220 nm); $\Delta E_{GS\text{-}ES}$ = 75 meV
6×10^{9} cm^{-2} (1290 nm); $\Delta E_{GS\text{-}ES}$ = 95 meV



Infrared Quantum Control Experiments on InAs Quantum Dots

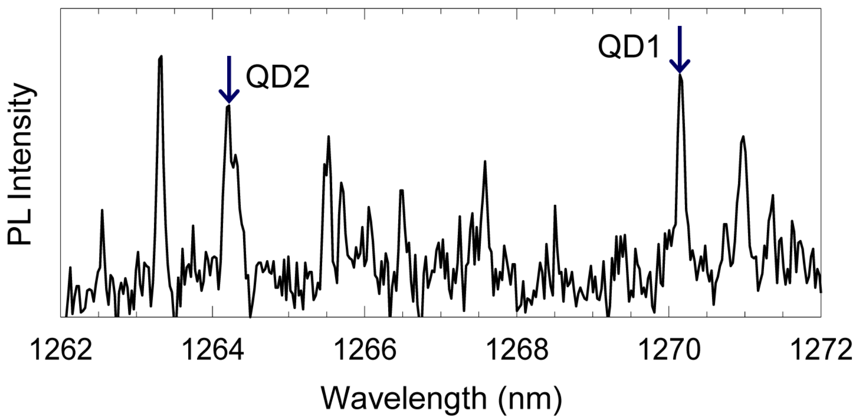
- Infrared laser source and pulse shaping system (OPO, 130 fs, 1.1-1.6 μm)
- Sample mounted on nanopositioner at 10 K in liquid helium flow-through cryostat
- Quantum state readout (PL) using 0.75 m monochromator and InGaAs array



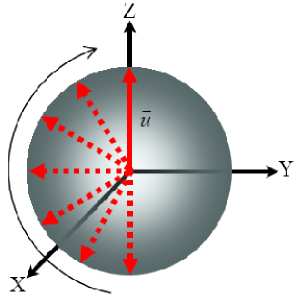


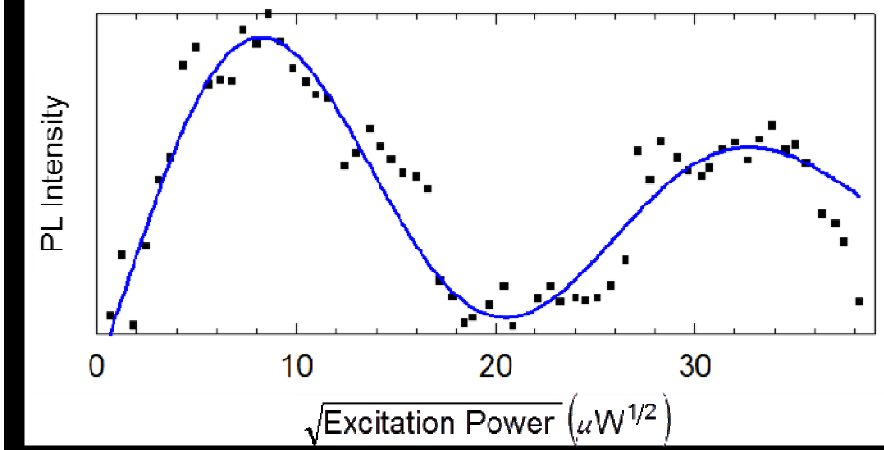
- p-shell control, s-shell quantum state readout
- Dipole moments and transition energies of QDs determined using PL and PLE for OQC

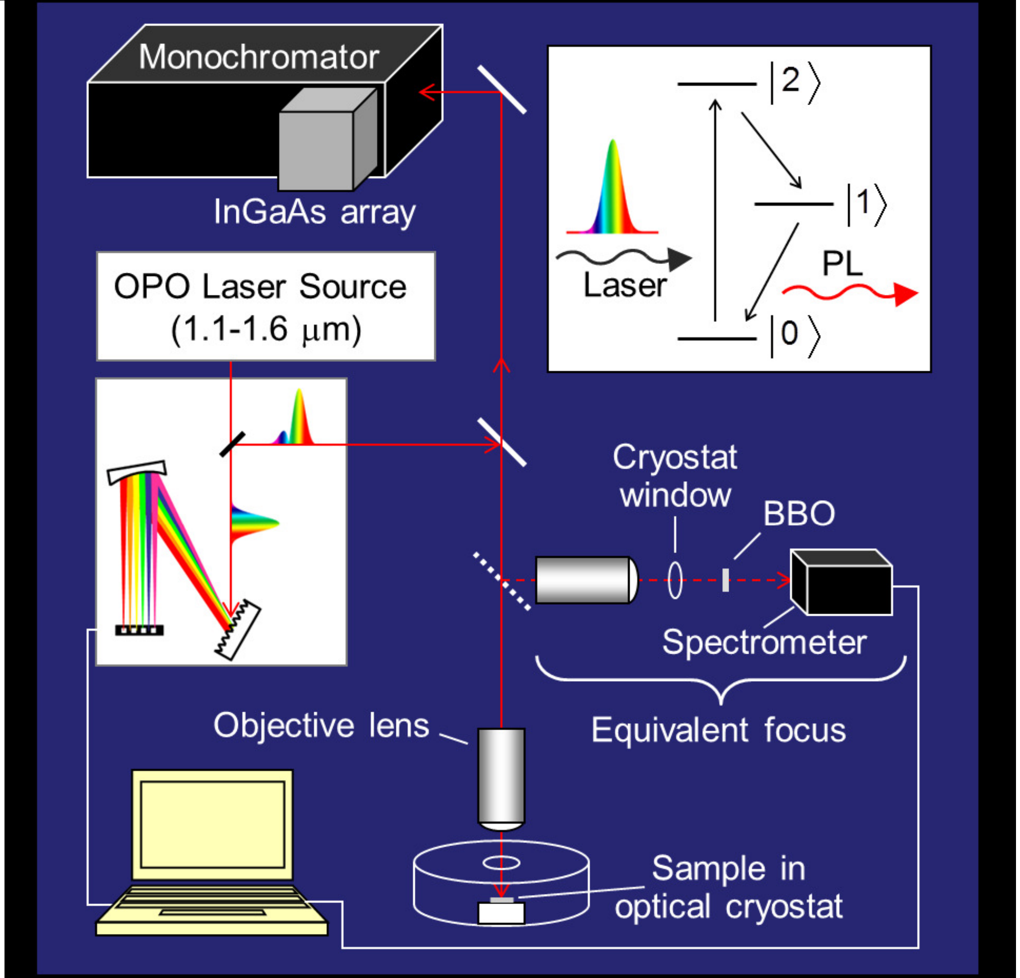
Infrared Quantum Control Experiments on InAs Quantum Dots



$$\theta(t) = \left(\frac{\mu}{\hbar}\right)\int_{-\infty}^{\infty} E_0(t)\,dt$$

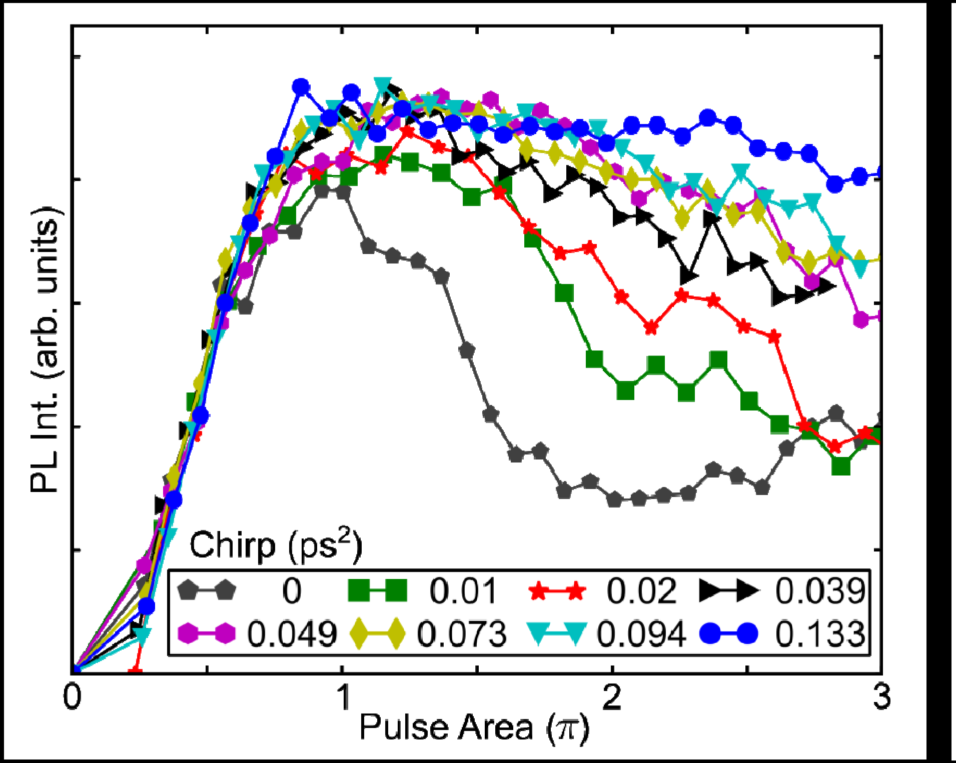


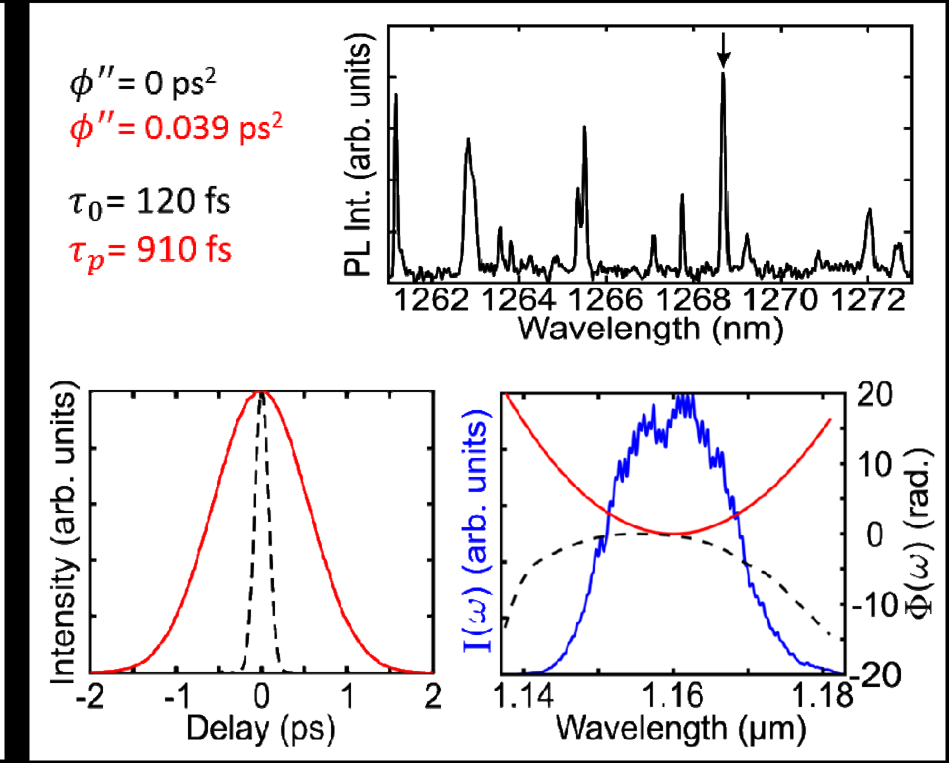




- p-shell control, s-shell quantum state readout
- Dipole moments and transition energies of QDs determined using PL and PLE for OQC

Subpicosecond Adiabatic Rapid Passage

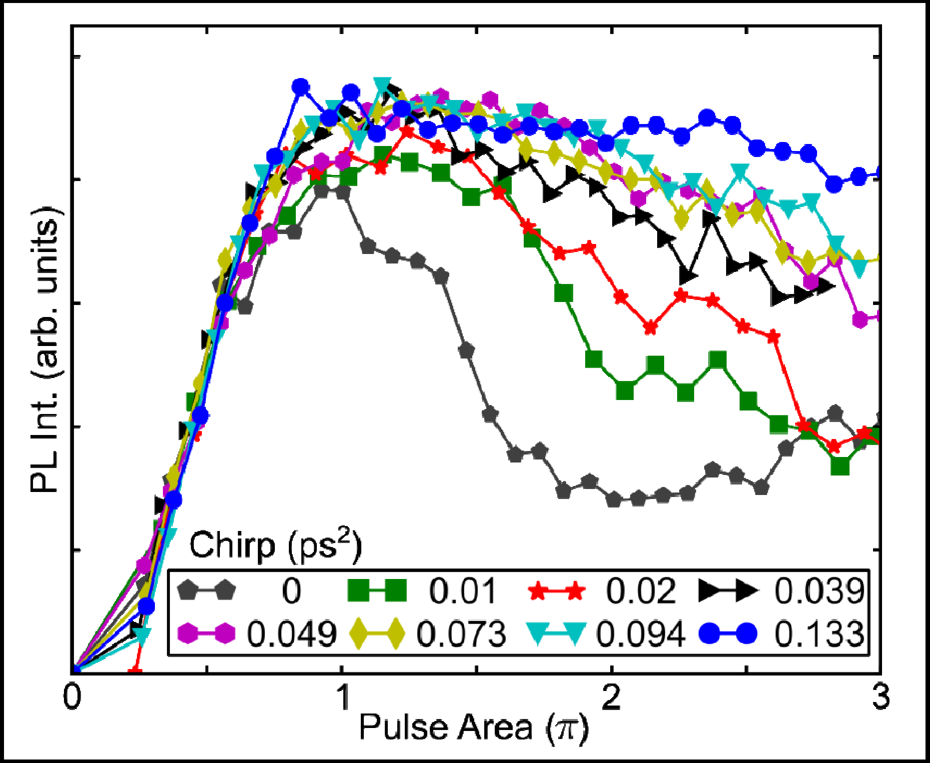




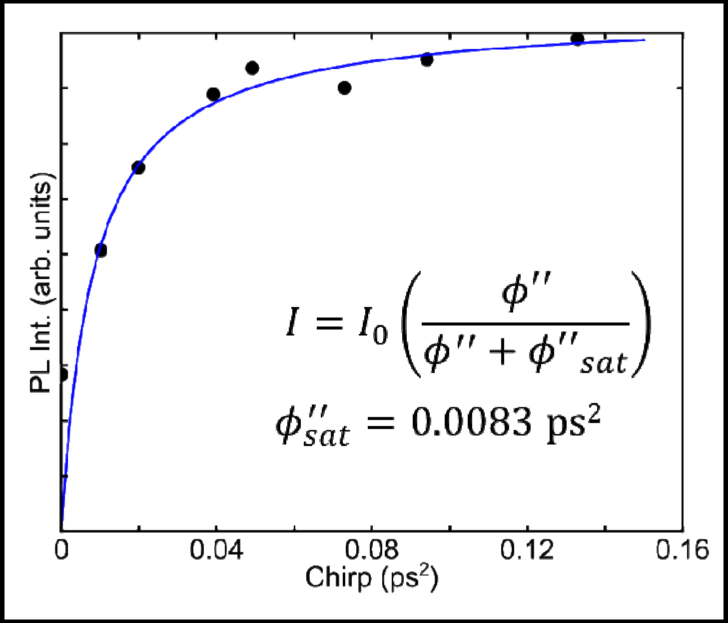
- Measure PL intensity as a function of pulse area for increasing positive spectral chirp (ϕ'')
- For $\phi'' = 0$, we observe a damped Rabi oscillation
- As $|\phi''|$ increases, the PL intensity increases for $\Theta > 2\pi$
- For $\phi'' = 0.133$ ps², PL intensity is nearly independent of pulse area.

Insensitivity to pulse area is a signature of ARP and robust state inversion

Subpicosecond Adiabatic Rapid Passage



- PL intensity at $\Theta = 2\pi$ shows saturation behaviour as a function of ϕ''

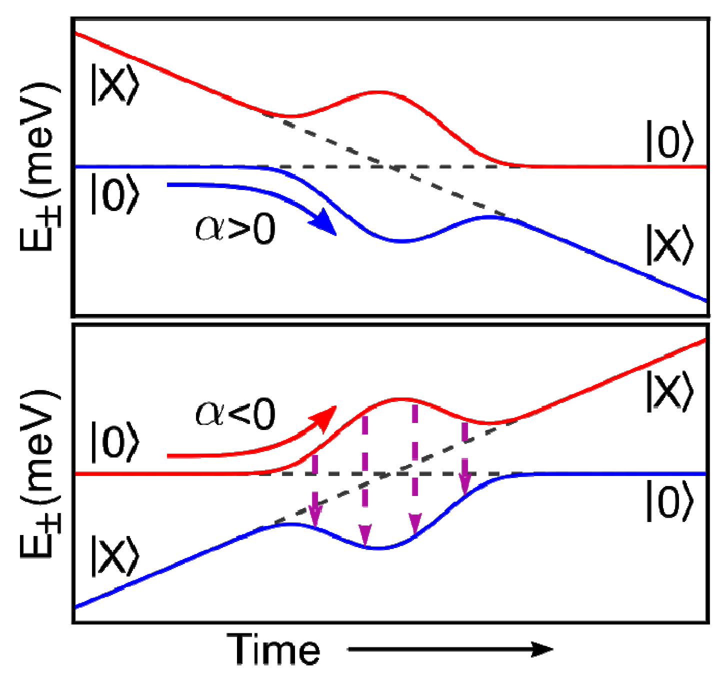


- We estimate the minimum chirp* required to achieve ARP to be **0.033 ps²**

  **Debnath et al., PRB 86, 161304(R) (2012),* $\phi''_{min} = \pi\tau_0^2/[2\ln(2)]$
- Use of broadband pulses results in lower threshold chirp (0.033 ps² vs. ~ 10 ps²)
- Chirped pulse width for ARP is: $\boldsymbol{\tau_p = 760}$ **fs**

A gate time reduction by factor of $\geq$ 20 relative to previous work

Role of Phonons in Strong-Driving Regime



- The use of subpicosecond control pulses puts our experiments into *a new regime of strong and rapidly-varying Rabi energy*

  - Importance of phonons in this new regime is not known

- If phonon processes are contributing, the efficiency of ARP should depend on the *sign of pulse chirp*. Chirp sign can be controlled using femtosecond pulse shaping techniques.

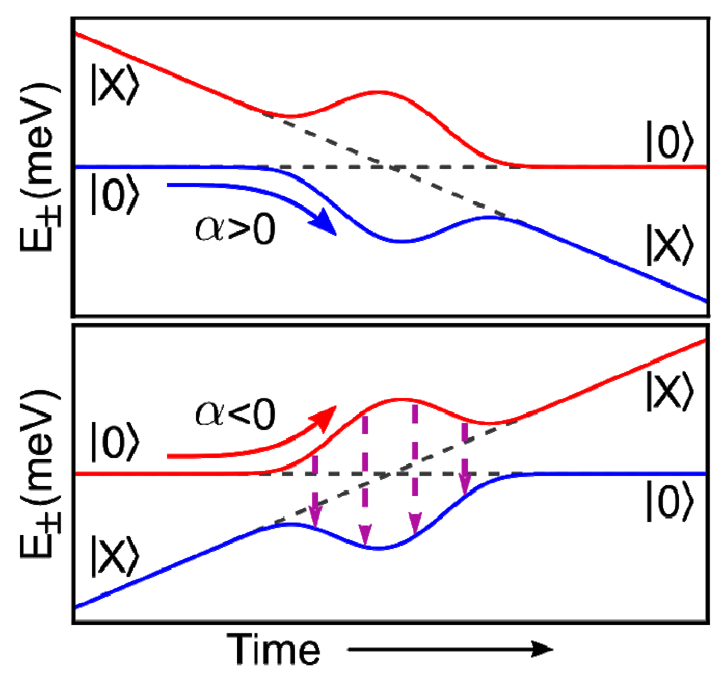
For $\alpha > 0$, diabatic transitions via phonon absorption are suppressed at 10 K
For $\alpha < 0$, diabatic transitions can occur due to phonon emission

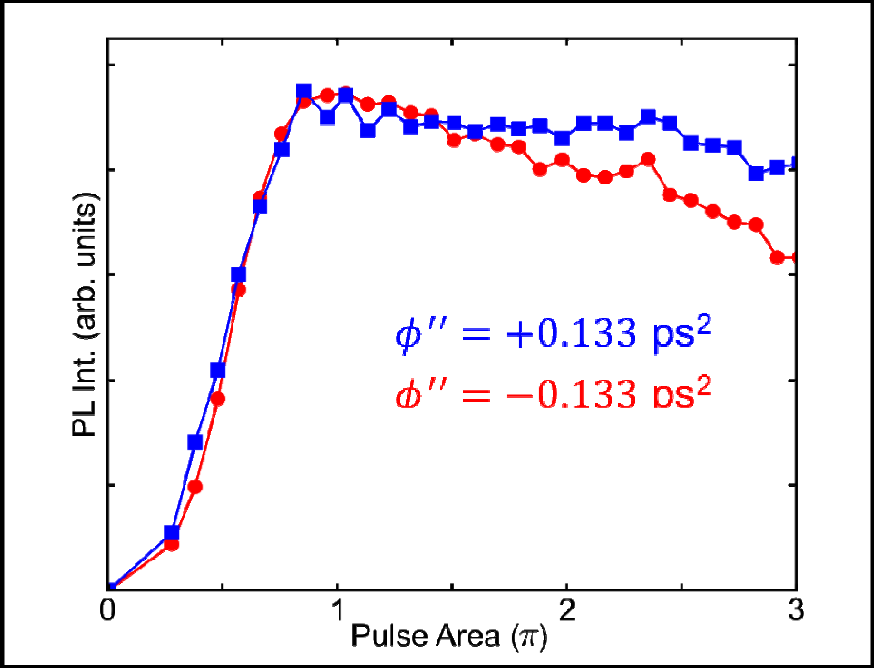
- Such a chirp sign dependence has been predicted theoretically but had not been demonstrated experimentally prior to this work.

Luker *et al.* PRB 85, 121302 (2012).
Debnath *et al.* PRB 86, 161304 (2012).

Reiter *et al.*
Acta Phys. Pol. A 122, 1065 (2012).

Role of Phonons in Strong-Driving Regime





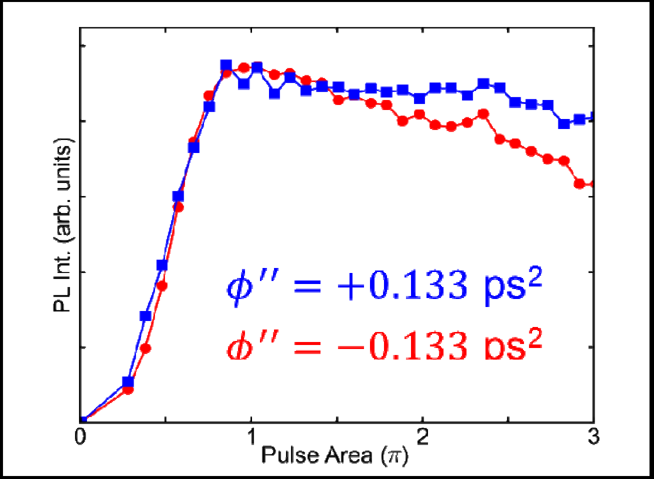
- Exciton occupation for <u>negative chirp is lower than that for positive chirp</u> by an amount that increases with increasing pulse area
- Results are independent of the polarization of control pulse

Experimental confirmation of predicted chirp sign dependence

Results indicate that coupling to phonons is primary mechanism limiting inversion via ARP and that <u>dephasing may be suppressed for positive chirp at low temperatures</u>

Role of Phonons in Strong-Driving Regime

- New insight into the transition between past ARP experiments and the new regime of strong and rapidly varying Rabi energy considered here

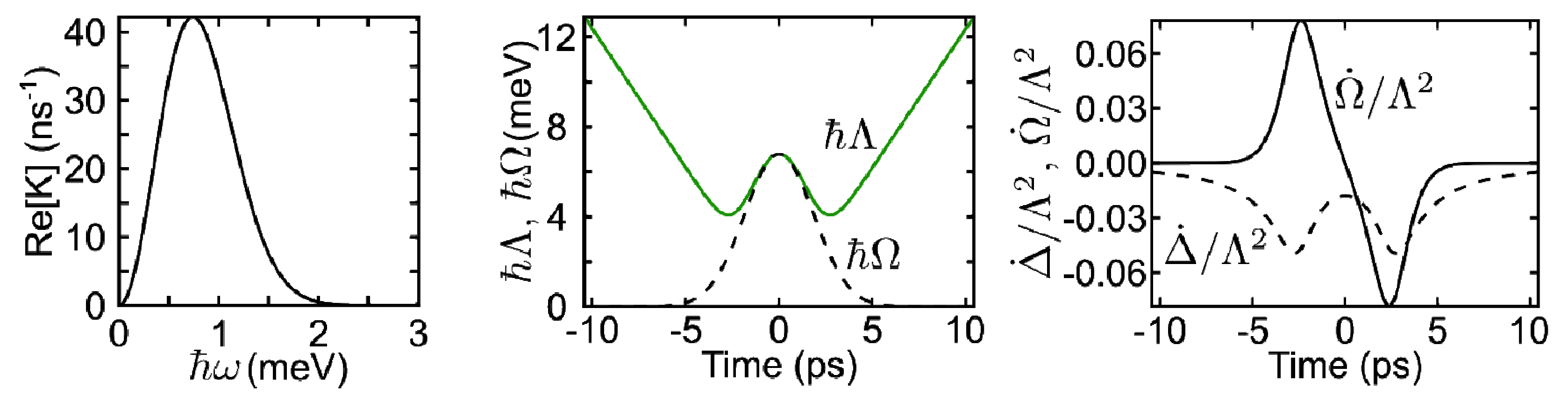


- We carry out numerical simulations of state evolution taking into account deformation potential coupling to longitudinal acoustic phonons

  Ramsay et al., J. Appl. Phys., 109, 102415 (2011).

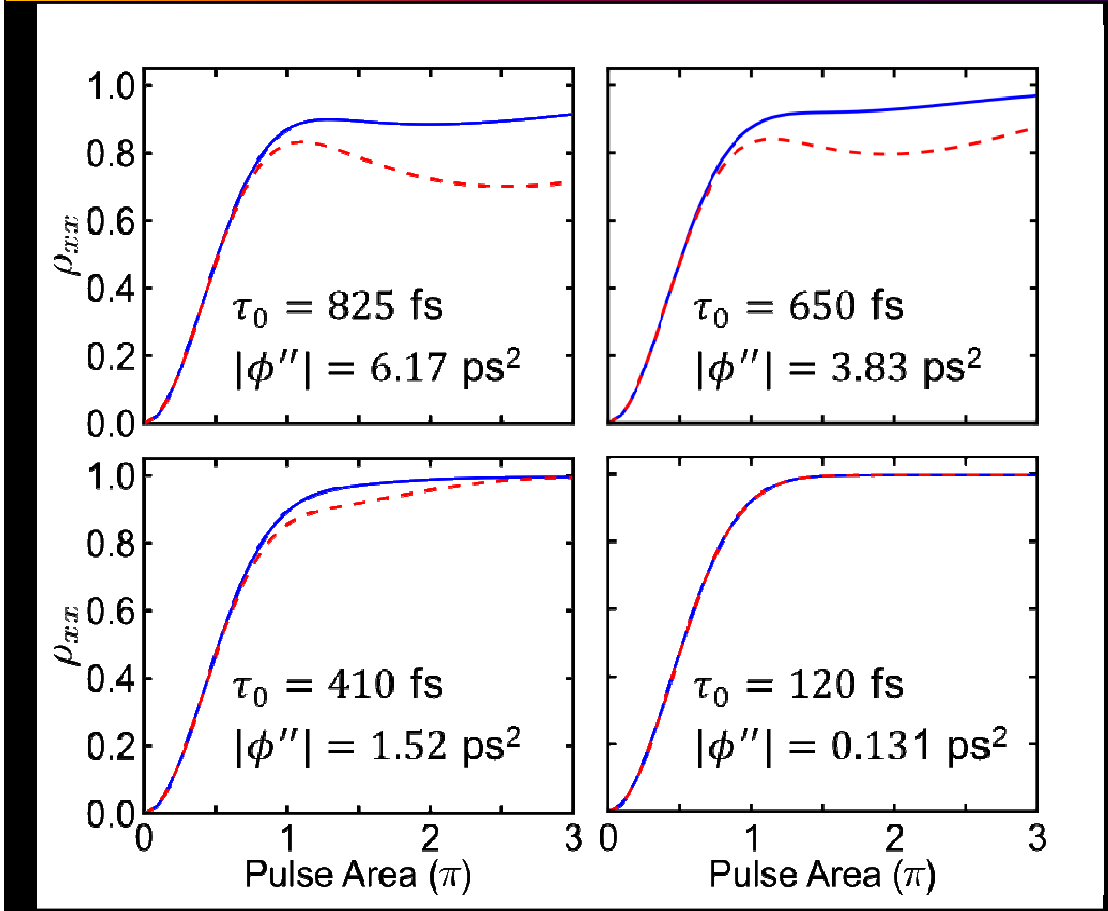
  Nazir, PRB 78, 153309 (2008)

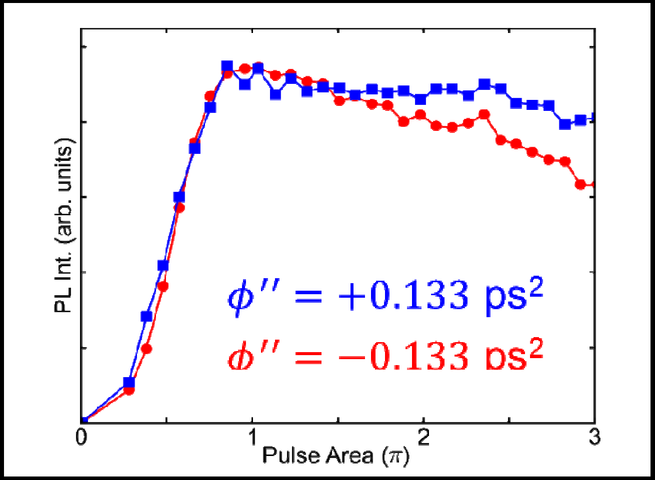
- $\mathrm{Re}[K(\hbar\Lambda)]$ is responsible for excitation-induced dephasing, where $K(\hbar\Lambda)$ is the complex response function of the electron-phonon coupling.



$\Lambda(\mathrm{t}) = \sqrt{\Omega(\mathrm{t})^2 + \Delta(t)^2}$ $\tau_0 = 120$ fs, $|\phi''| = 0.133\ \mathrm{ps}^2$

Role of Phonons in Strong-Driving Regime





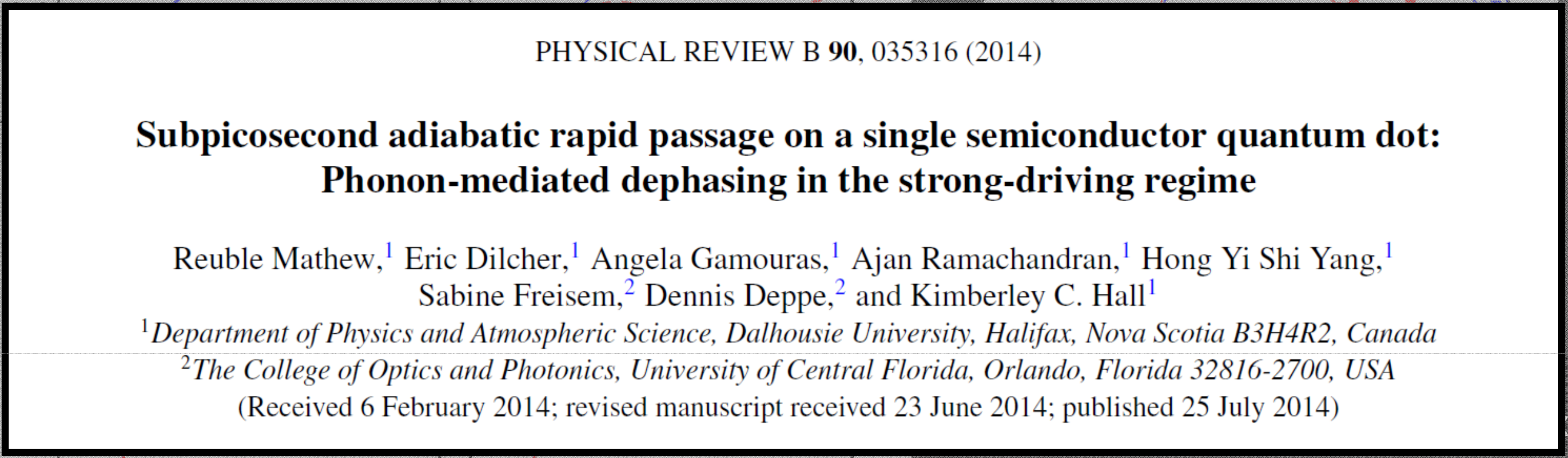
Study transition between past ARP expts and the regime of strong and rapidly varying Rabi energy

- Results are shown for increasing bandwidth with $\phi'' = 4\phi''_{min}$

- Model predicts decoupling from the environment for large Rabi energies. We observe a persistence of phonon mediated dephasing despite large $\Lambda(\mathrm{t})$.

Suggests that other physical processes not included in this model may play a role.
E.g. **multi-phonon processes, piezoelectric coupling, non-Markovian effects**

Role of Phonons in Strong-Driving Regime



PHYSICAL REVIEW B **90**, 035316 (2014)

Subpicosecond adiabatic rapid passage on a single semiconductor quantum dot: Phonon-mediated dephasing in the strong-driving regime

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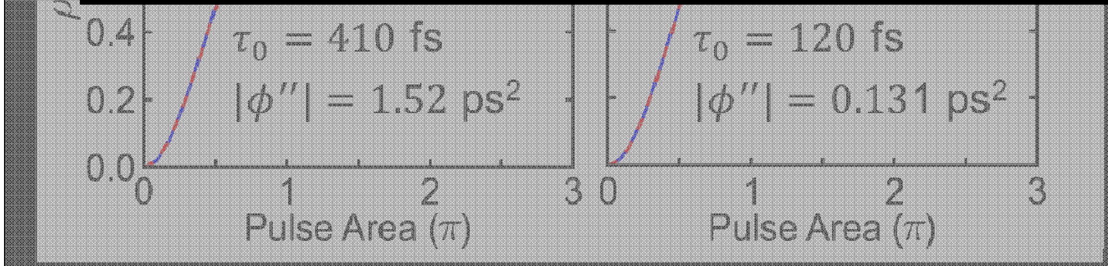

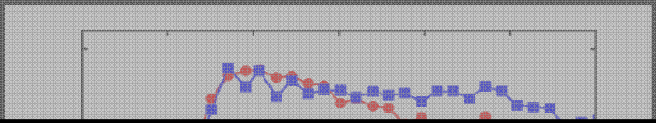

approach

- Results are shown for increasing bandwidth with $\phi'' = 4\phi''_{min}$

- Model predicts decoupling from the environment for large Rabi energies. We observe a persistence of phonon mediated dephasing despite large $\Lambda(t)$.

Suggests that other physical processes not included in this model may play a role. *E.g.* multi-phonon processes, piezoelectric coupling, non-Markovian effects

Conclusions

- Our experiments explore a new regime of strong (and rapidly varying) Rabi energies, providing new insight into the role of phonons in dephasing.
- We demonstrated ARP using subpicosecond control pulses: 20 x reduction in gate time relative to previous work.
- Phonon-mediated EID may be suppressed for positive pulse chirp at low tempertures by maintaining the quantum system in the lower-energy adiabatic branch during the control process.

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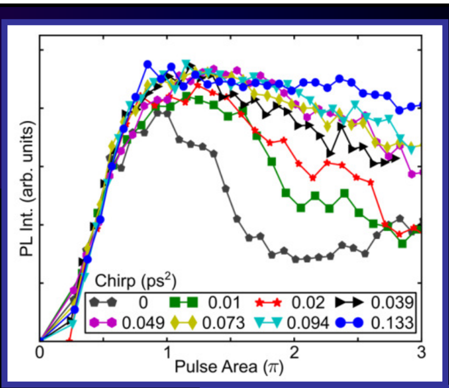

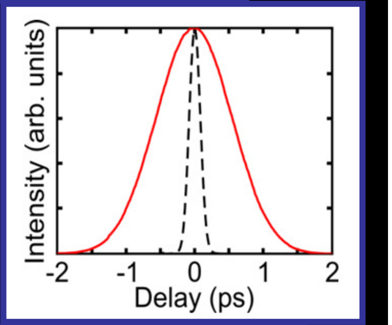

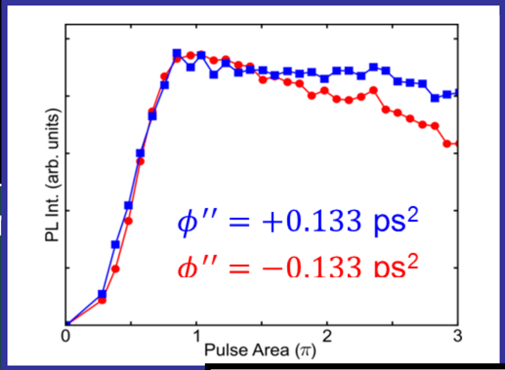

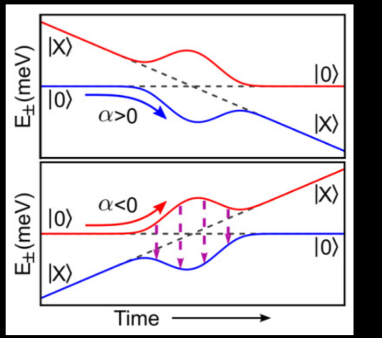

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