Rabi oscillations of impurity-bound electrons in semiconductors

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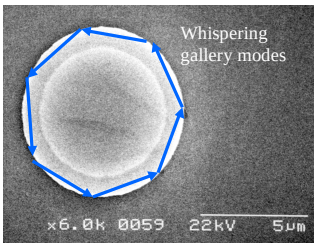
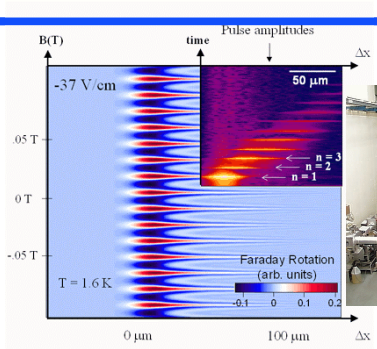
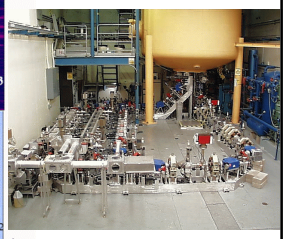
Quantum Information Research at UCSB





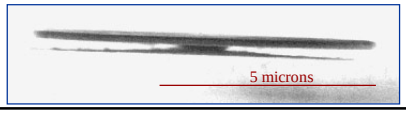


Quantum Optics with Quantum Dots (A. Imamoglu group)

Manipulation of Electron and Nuclear Spins in Semiconductors with Interband Light (D. D. Awschalom group)

Manipulation of 3-D Confined Electrons with terahertz radiation (M. S. Sherwin group)

Materials and processing: Evelyn Hu, Pierre Petroff, Art Gossard groups



Acknowledgments

- Collaborators:
  - Dr. Bryan Cole (Now at Toshiba, Cambridge)
  - Jon Williams (Ph. D. 2000, now post-doc at Caltech)
  - Sean Roy (undergraduate, now string theorist at Stanford)
  - Dr. Tom King (post-doc)
  - Matt Doty (Ph. D. student)
  - Prof. Colin Stanley (U. of Glasgow)
  - Dr. Philippe Boucaud (Centre d'Electronique Fondamentale)
  - Kohl Gill (Ph. D. student)
  - Dr. W. Schonfeld
  - Prof. P. Petroff
  - Nathan Jukam (Ph. D. student)
  - Prof. Atac Imamoglu
  - Prof. D. D. Awschalom
- Support:
  - DARPA, ARO.

Rabi osc. impurities.

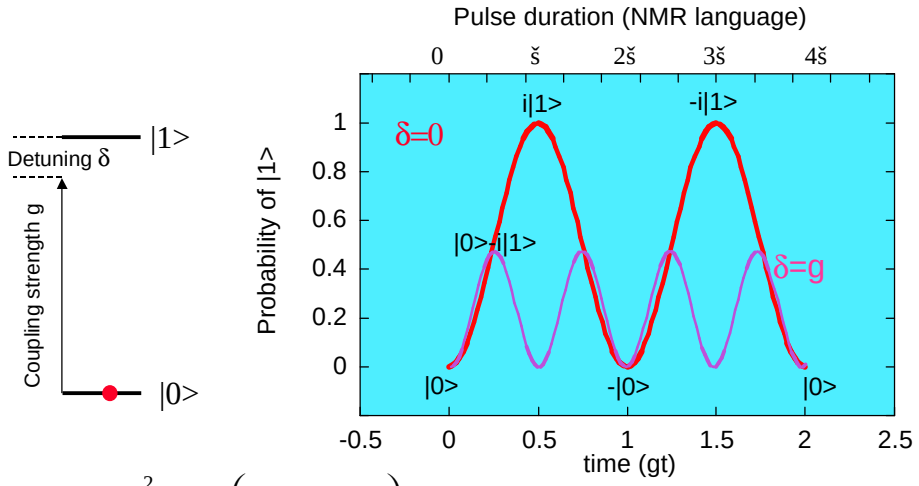
THz Absorption Q. Dots

THz resonators

Outline

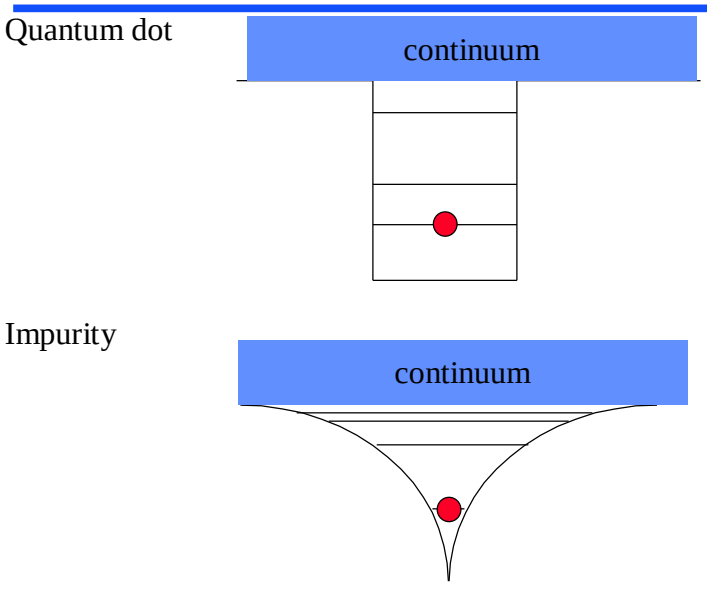
- Two-state systems and quantum bits
- Observation of Rabi oscillations in a doped semiconductor
- Implications for quantum information processing

Two-state system in an oscillating field

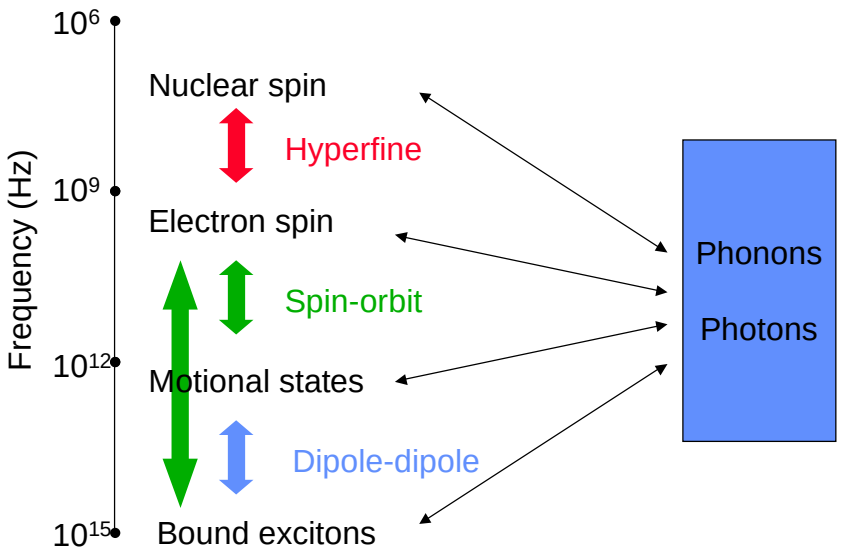


$$P_{01}(t) = \frac{g^2}{g^2+\delta^2}\sin\left(\sqrt{g^2+\delta^2}\,\frac{t}{2}\right)$$

Bound electrons in semiconductor

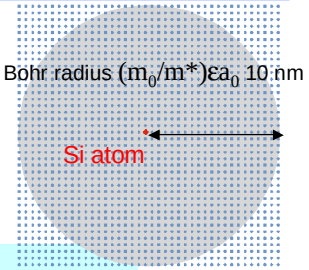


~Two-state systems in semiconductors

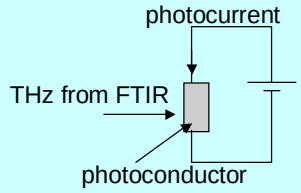


Hydrogenic donors

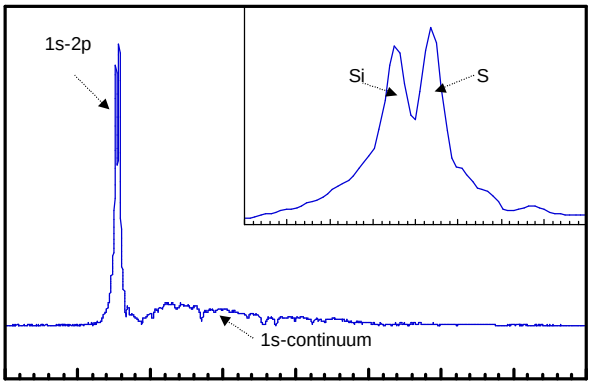
- Example: Si in GaAs
- Effective mass approx.: H atom w.
  - m-> m*=0.067
  - Dielectric const. -> 13
  - Ry->Ry*~ (m^*/m_0) $(1/\varepsilon^2)$13.6 eV ~4 meV



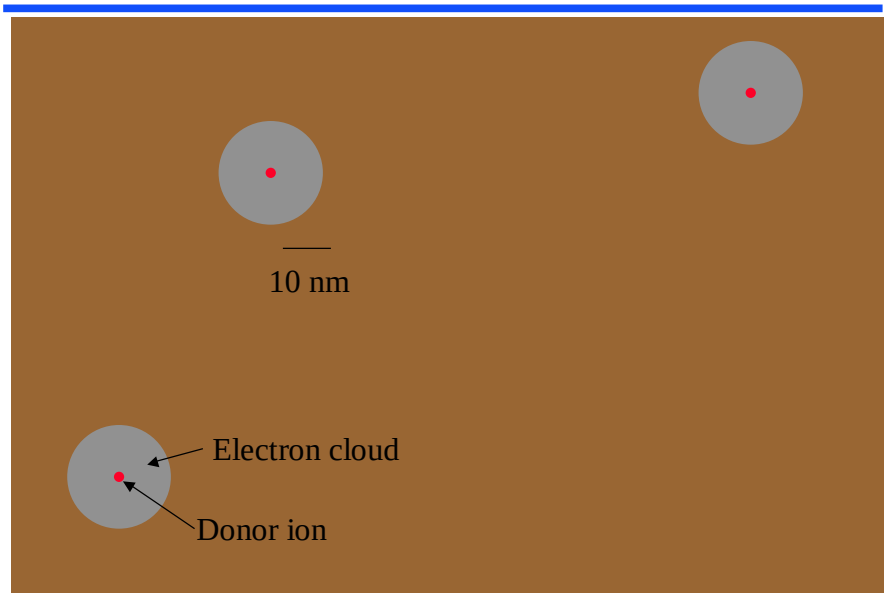
- Samples & experiment
  - Epitaxial GaAs, N_D-N_A=10^{14} cm^{-3}
  - From Prof. Colin Stanley, U. Glasgow



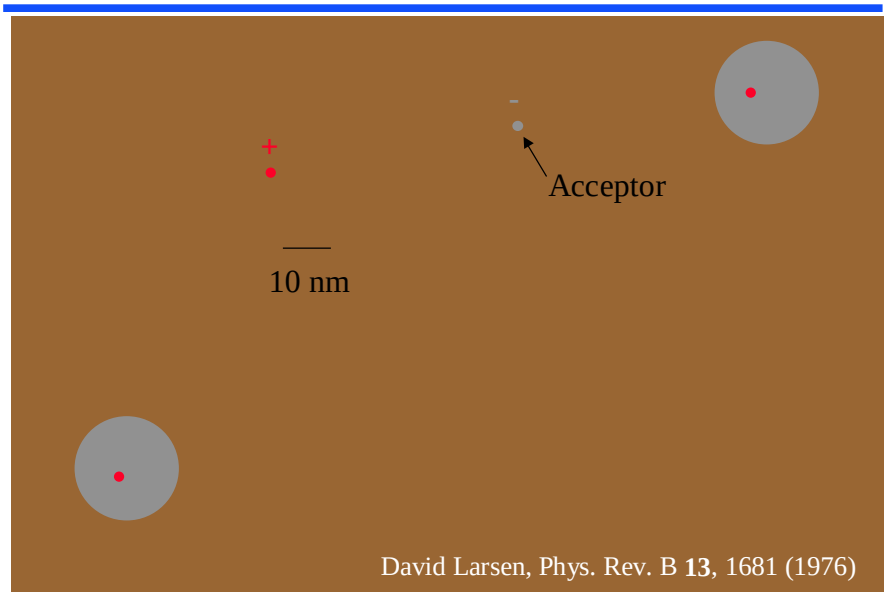
Photocurrent spectrum, GaAs (B=0)



Donors only

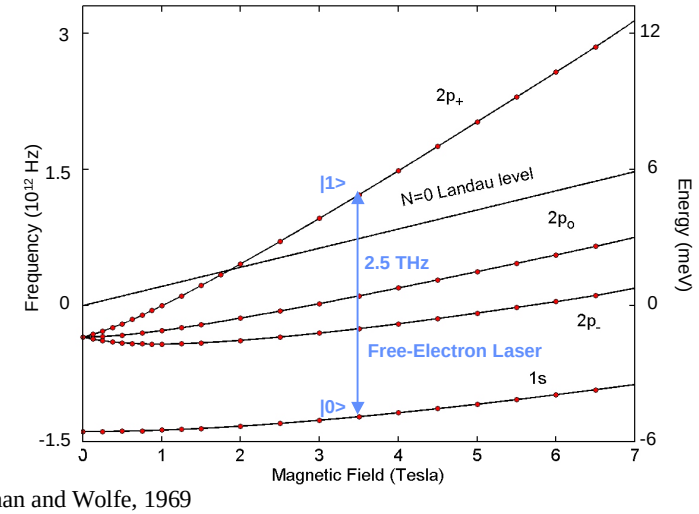


Donors and acceptors: inhomogeneous broadening



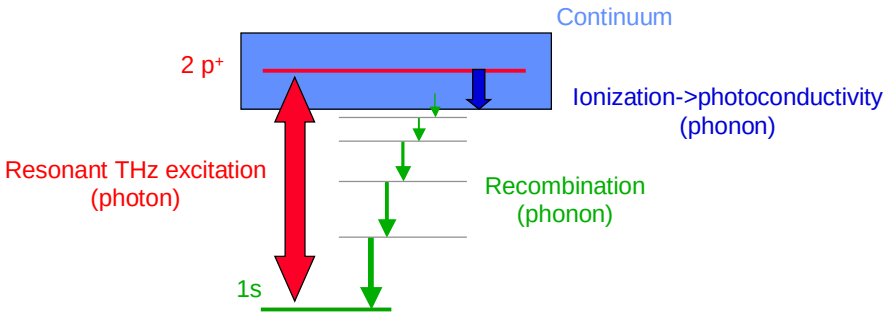
David Larsen, Phys. Rev. B **13**, 1681 (1976)

B-dependence of Hydrogenic levels in GaAs



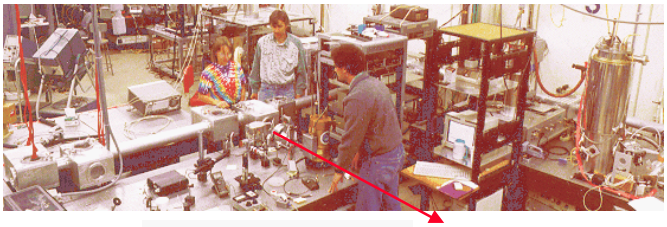
Data: Stillman and Wolfe, 1969
Calculations: B. Tom King (following Larsen, 1968)

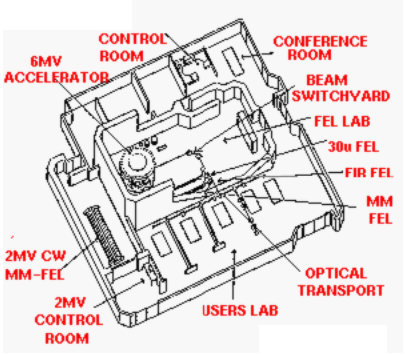
Mechanism for resonant photoresponse



The UCSB free-electron laser and user lab

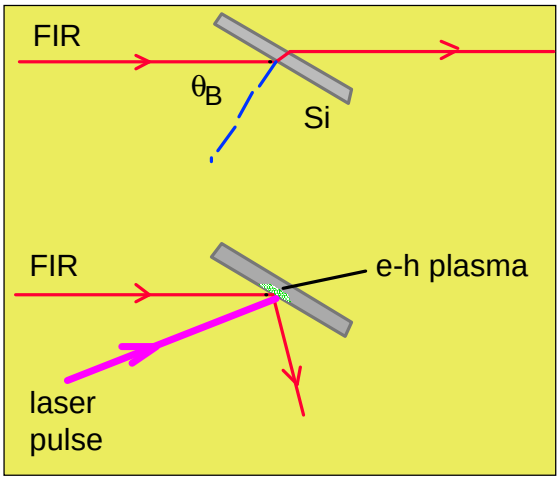
UCSB Free-Electron Lasers

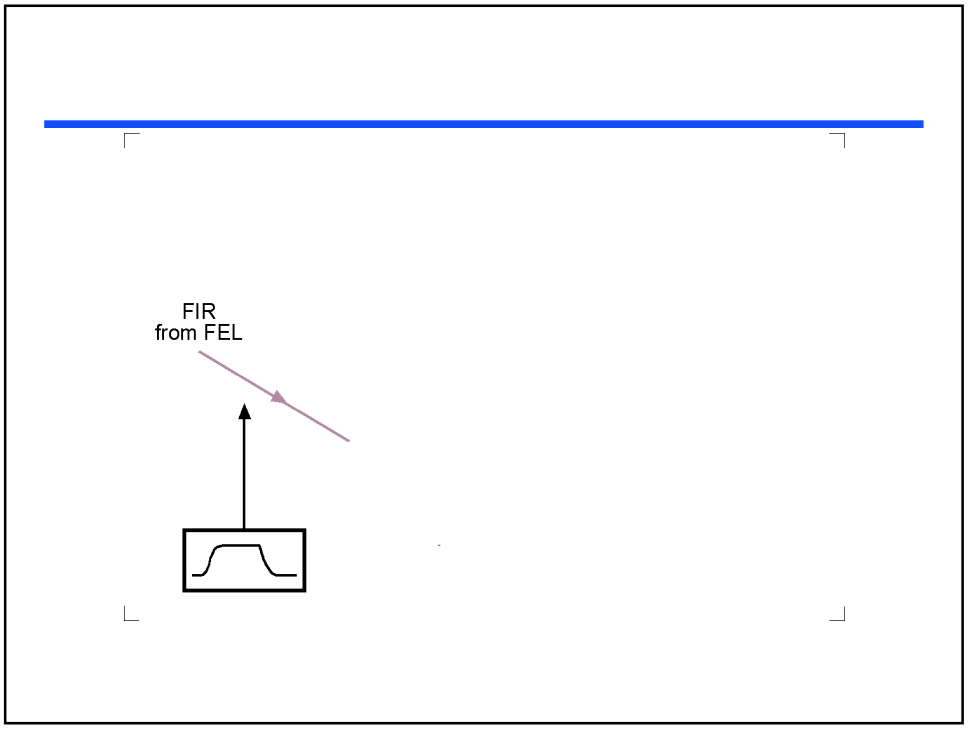


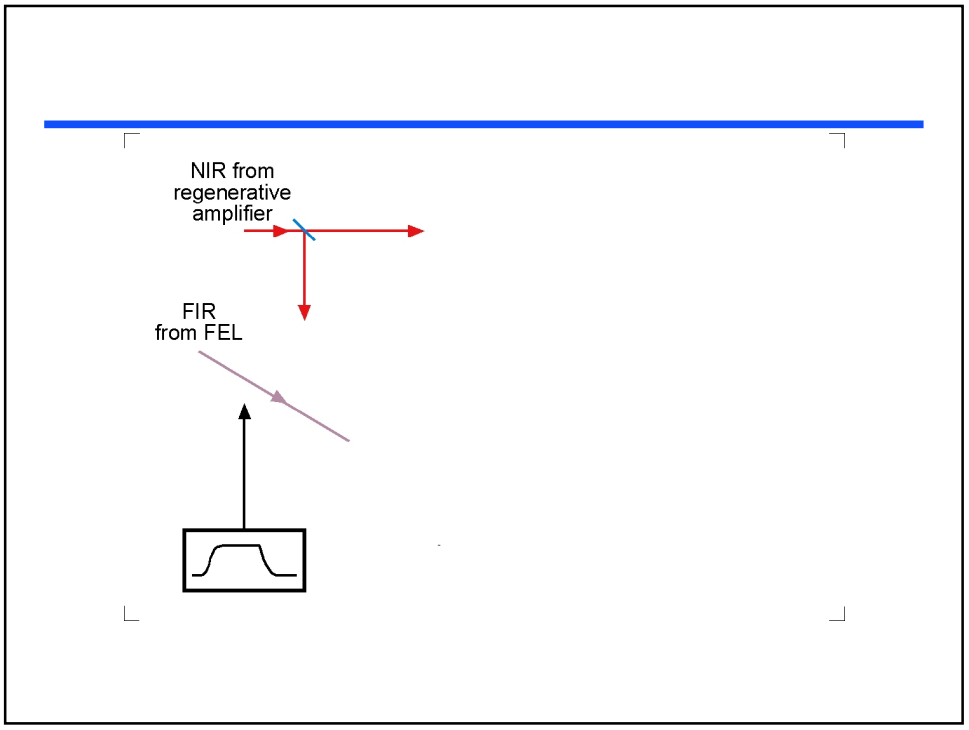


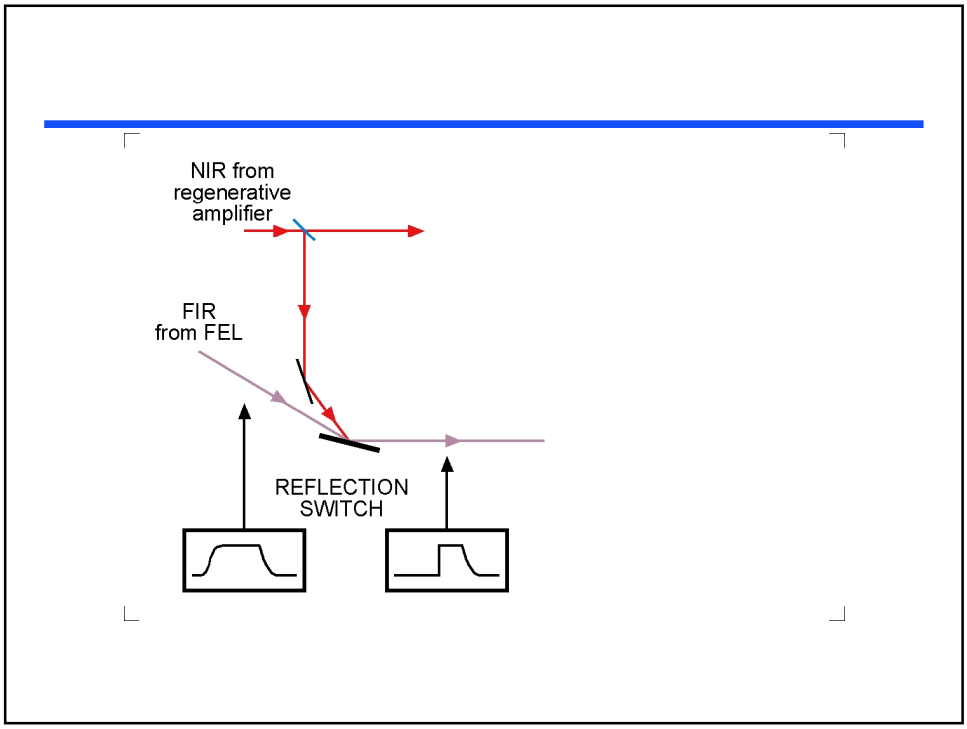
- $0.12 - 4.8 \times 10^{12}$ Hz
  (0.5-20 meV, 4-160 cm^{-1})
- 500W - 5 kW peak power
- 1-20 μs pulse duration
- 4 Hz repetition rate

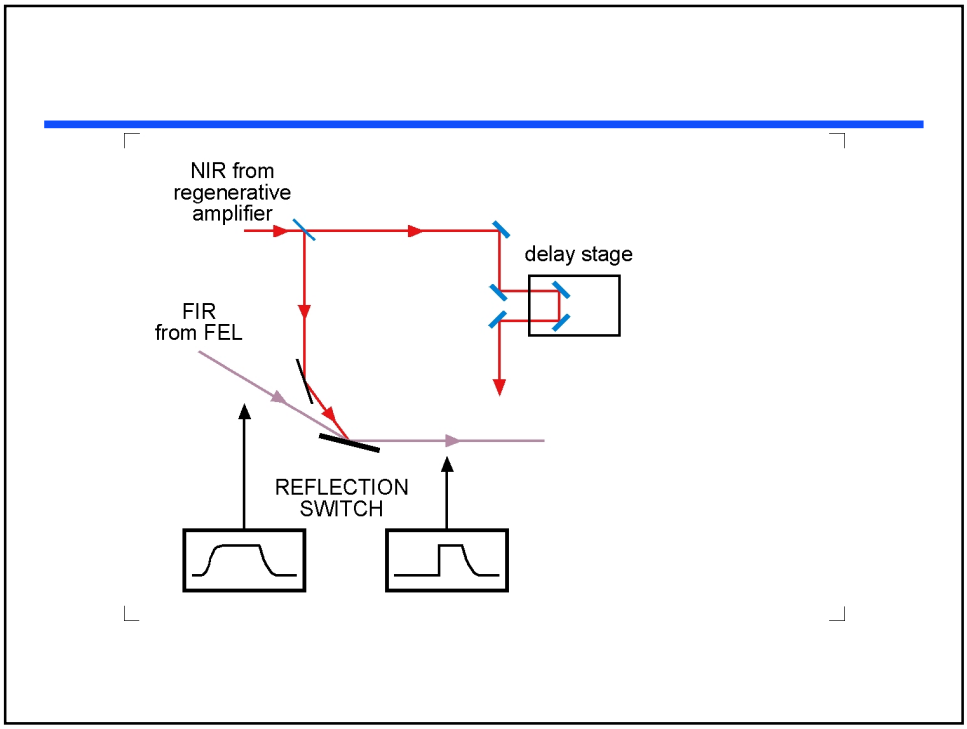
ps-to-ns pulse generation: light-activated semiconductor switches

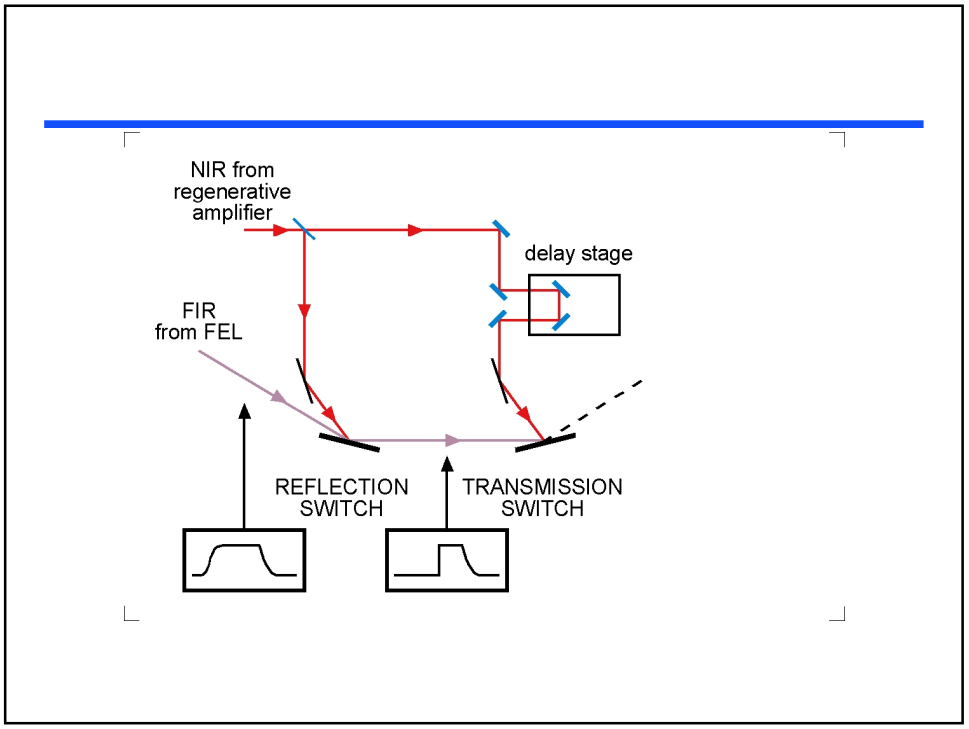


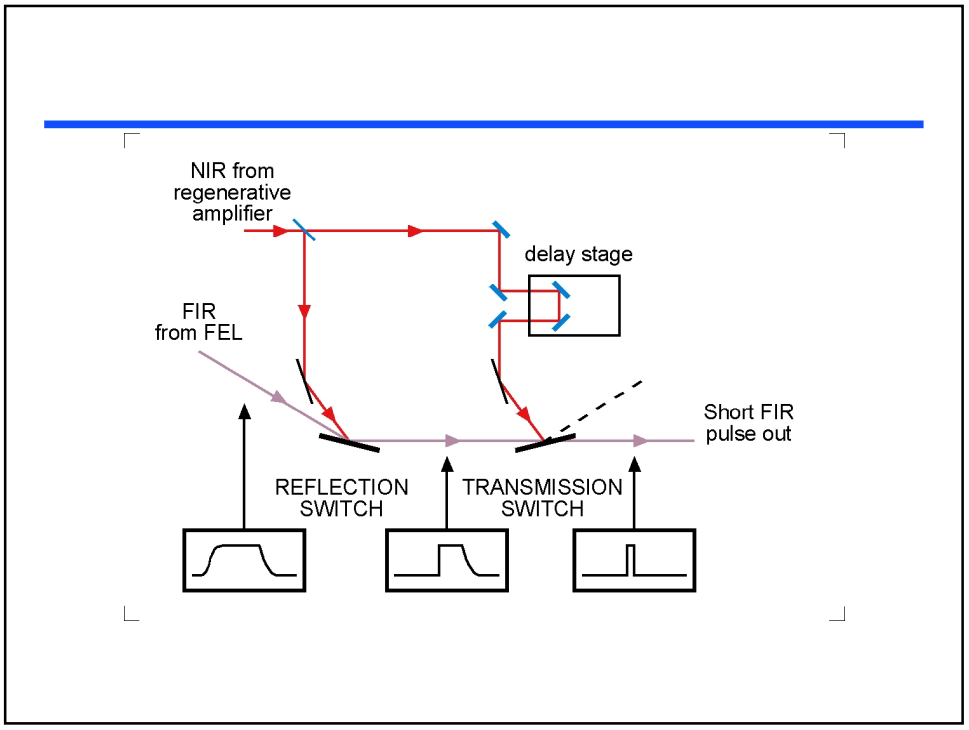

FIR
from FEL


NIR from
regenerative
amplifier
FIR
from FEL


NIR from
regenerative
amplifier
FIR
from FEL
REFLECTION
SWITCH


NIR from
regenerative
amplifier
delay stage
FIR
from FEL
REFLECTION
SWITCH

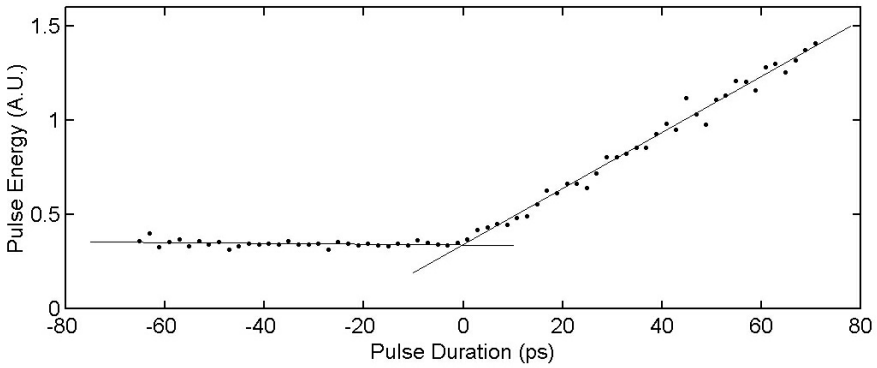

NIR from
regenerative
amplifier
delay stage
FIR
from FEL
REFLECTION
SWITCH
TRANSMISSION
SWITCH


NIR from
regenerative
amplifier
delay stage
FIR
from FEL
Short FIR
pulse out
REFLECTION
SWITCH
TRANSMISSION
SWITCH

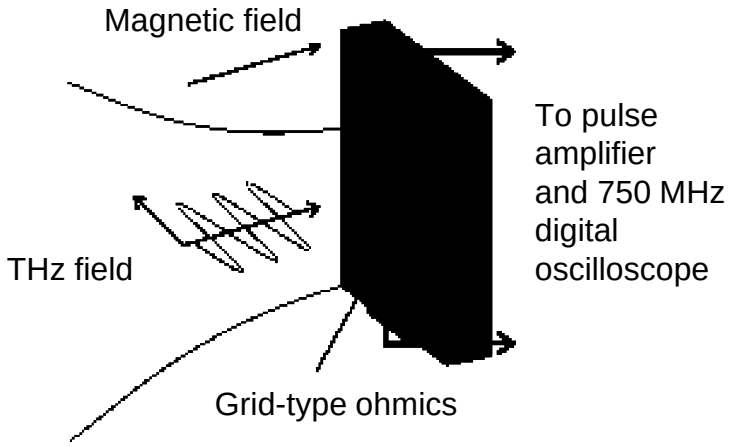
"Sliced" pulses

F. A. Hegmann et. al., Appl. Phys. Lett. **76**, 262 (2000)

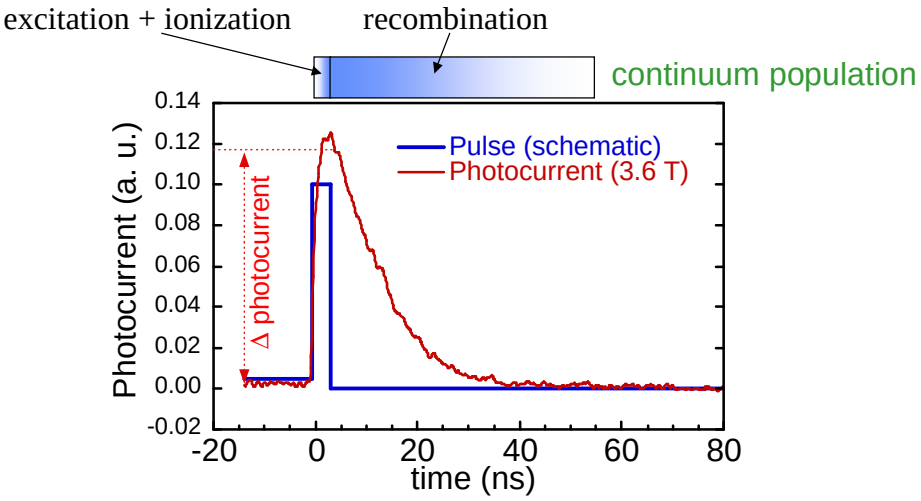
Pulse energy vs. pulse duration



Sample geometry

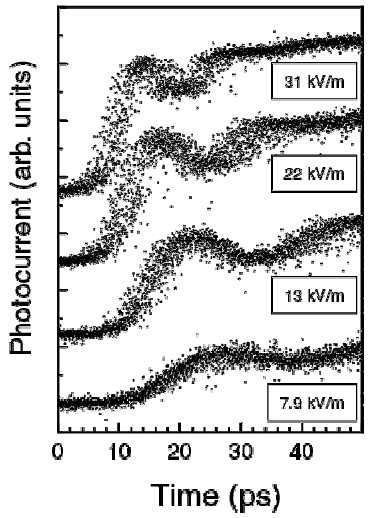


Single photocurrent pulse



Rabi oscillation

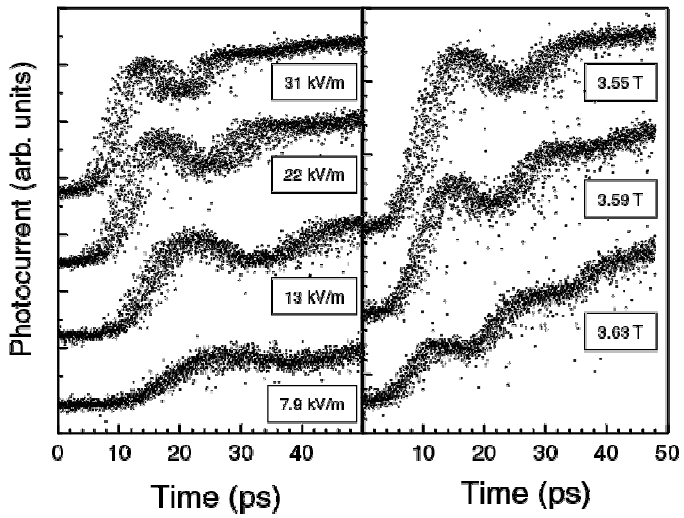
Dependence on THz electric field



Rabi oscillation

Dependence on detuning

Resonant



Density Matrix Model

- Equations
  - 1s: |1>
  - $2p^+$: |2>
  - γ_1: population relaxation rate
  - γ_2: dephasing rate
  - γ_3: ionization rate
  - *Initial conditions:*
    $\rho_{11}(\tau=0)=1,\ \rho_{12}(0)=\rho_{22}(0)=0$

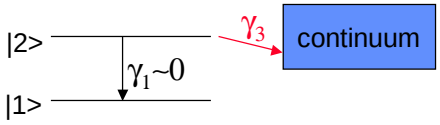
$$\dot{\rho}_{11} = \frac{1}{i\hbar}[H,\rho]_{11} + \gamma_1\rho_{22}$$

$$\dot{\rho}_{22} = \frac{1}{i\hbar}[H,\rho]_{22} - \gamma_1\rho_{22} - \gamma_3\rho_{22}$$

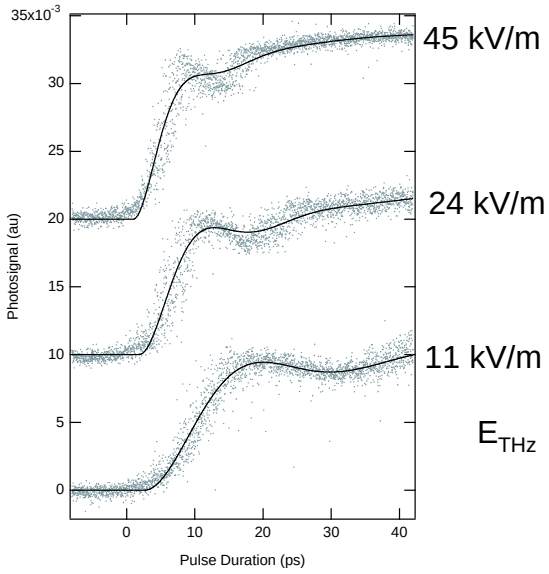
$$\dot{\rho}_{12} = (\dot{\rho}_{12})^* = \frac{1}{i\hbar}[H,\rho]_{12} - \gamma_2\rho_{12}$$

$$H = H_0 + e\vec{E}_{THz}(t)\bullet\vec{x}$$

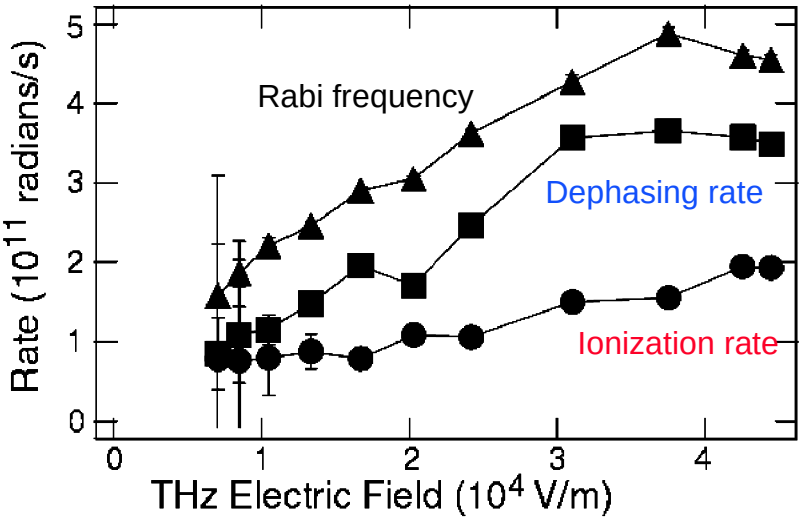
$$\text{photocurrent signal} \propto (1-\rho_{11}(\tau))$$



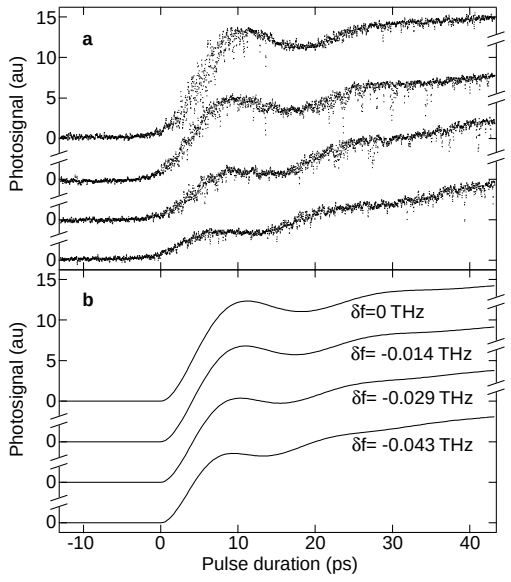
Power dependence of Rabi oscillation



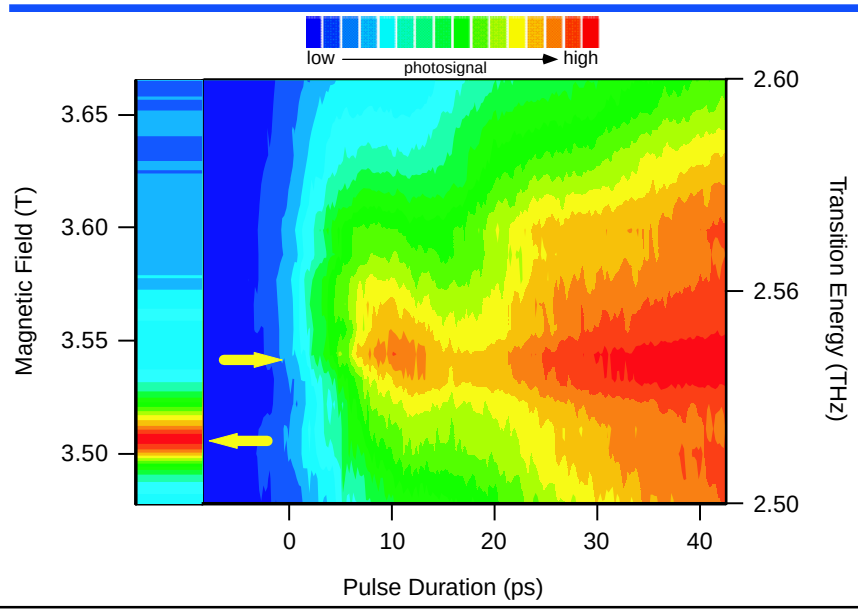
Resonant rabi frequency, dephasing and ionization rates vs. THz electric field



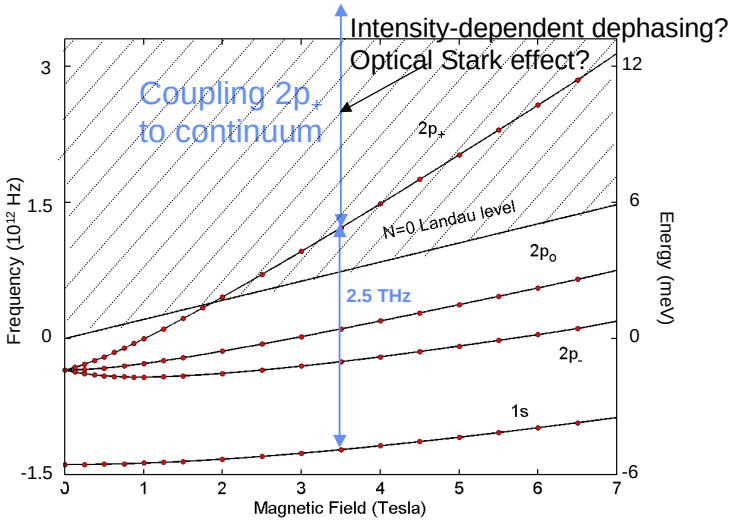
Rabi frequency vs. field, detuning



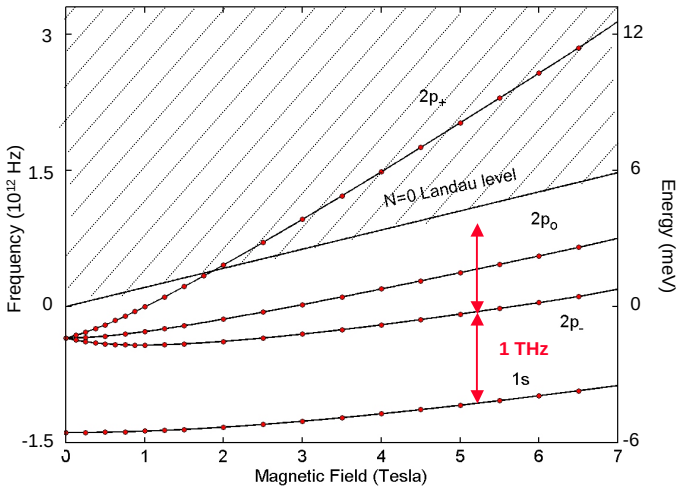
Photosignal vs. pulse duration, B



Effect of continuum

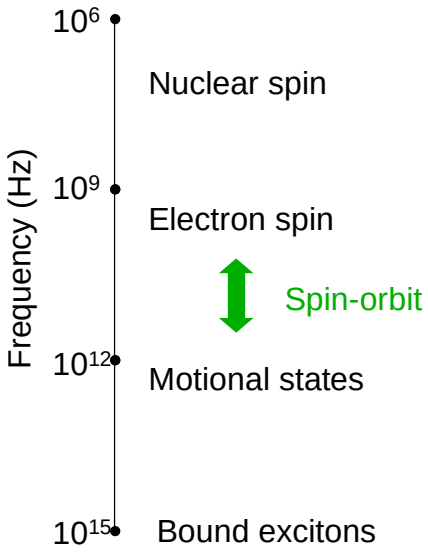


Experiments under way

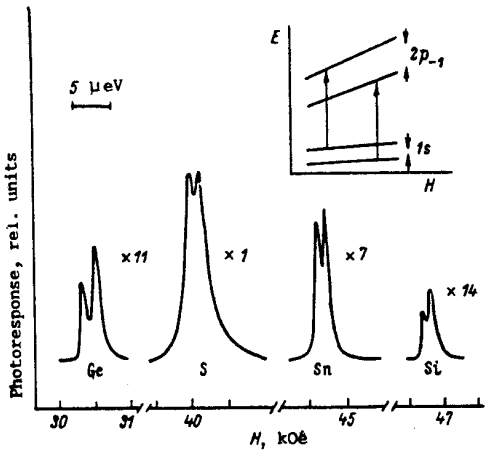


$2p_-$ state no THz-induced decoherence ->many Rabi oscillations

~Two-state systems in semiconductors

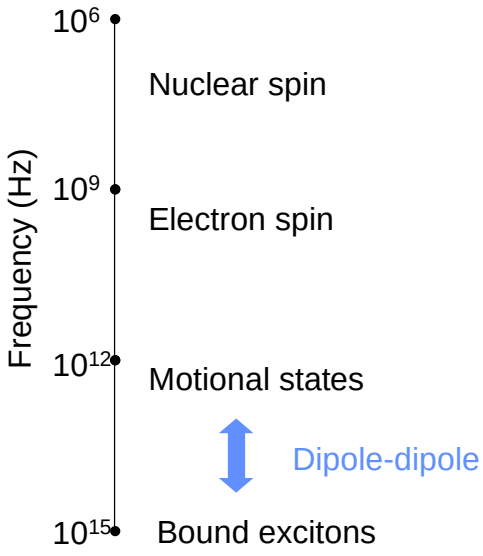


Spin-orbit splitting of 1s-2p$_-$ transition

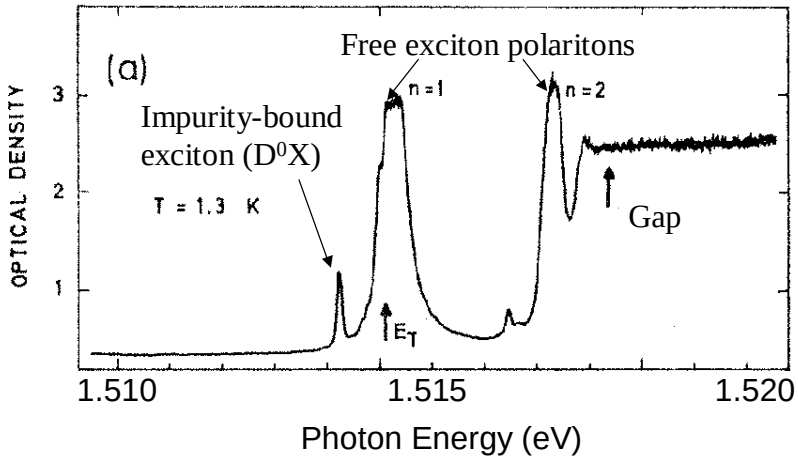


V. G. Golubev et. al., Sov. Phys. Semic. **21**, 18 (1987)

~Two-state systems in semiconductors

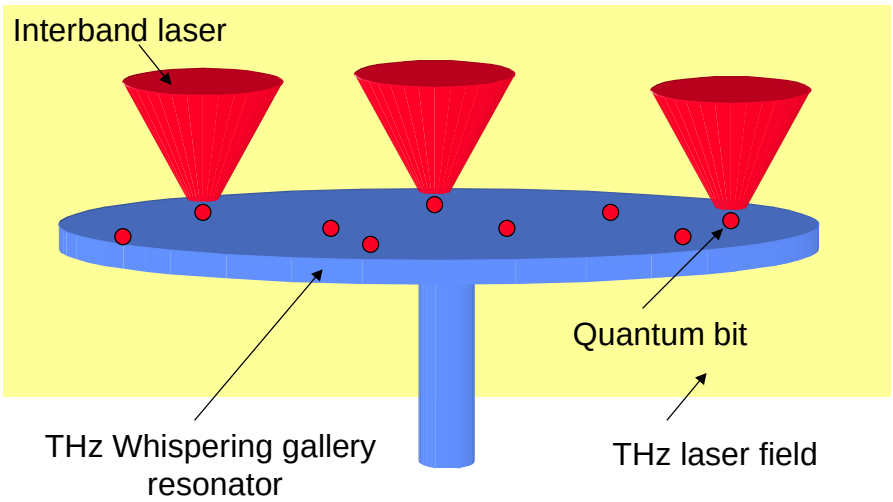


Absorption of high-purity GaAs



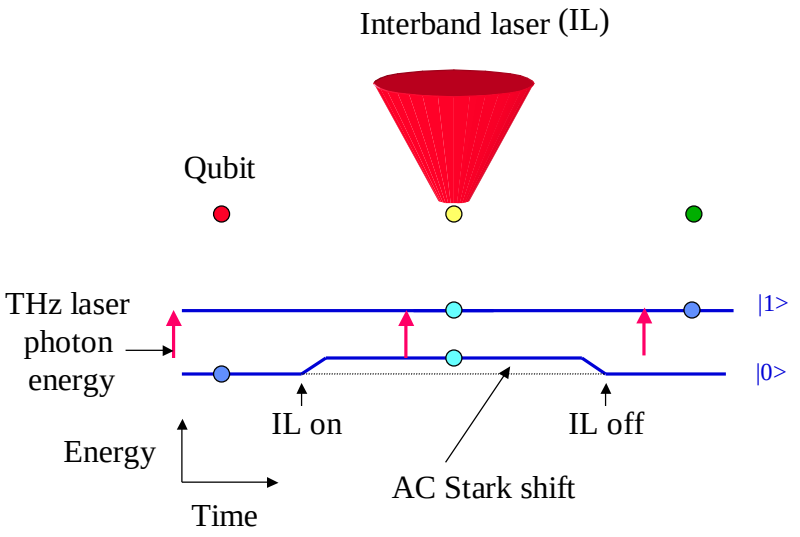
3.7 μm thick sample R. G. Ulbrich and G. W. Fehrenbach, Phys. Rev. Lett. **43**, 963 (1979)

All-optical semiconducting quantum computer



Sherwin, Imamoglu, Montroy, Phys. Rev. A60, 3508 (1999)
Imamoglu et. al., PRL 83, 4204

Example of local 1-bit operation: "π-pulse"



Theoretical opportunities, figure of merit

- "First-principles" modeling of experimental data
  - Intensity-dependent dephasing
  - Intensity-dependent frequency
- Realistic calculations of decoherence rates--how long can they be?
  - Nishikawa and Barrie (1962(!))
    - $T_2 \sim 5 \times 10^{-9}$ s (B=0, T=0).
  - Max. observed Rabi frequency (2001)
    - $\Omega = 5 \times 10^{11}$ Radians/s. (B=3.5 T, T=2K)
- How many Rabi oscillations w. o. extrinsic dephasing?
  - $\Omega T_2 = 2500$?

References

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- K. Nishikawa and R. Barrie, "Phonon broadening of impurity spectral lines," *Canadian Journal of Physics* **41**, 1135 (1963).
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- D. M. Larsen,"Inhomogeneous broadening of the Lyman-series absorption of simple Hydrogenic donors," *Phys. Rev. B* **13**, 1681 (1976)
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