Single spin readout and initialization in a quantum dot

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Quantum Dot Quantum Computers

[Loss/DiVincenzo, PRA]

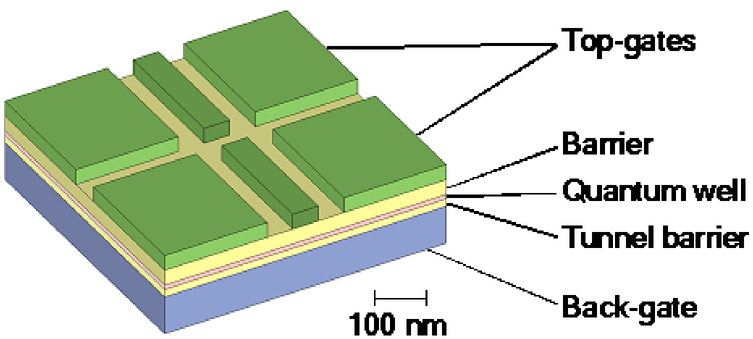
SiGe or GaAs heterostructure with trapped electron spin as qubit

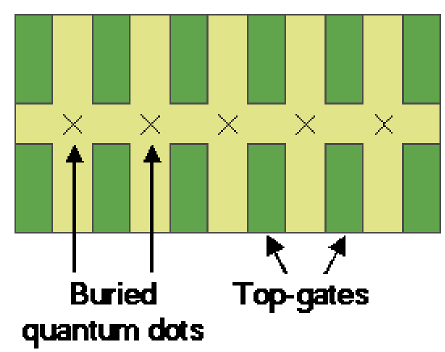
- low decoherence
- potentially scalable, fast
- 1&2-qubit operations via exchange

Fundamental challenges:

- Single spin readout
- Efficient initialization of qubits

We propose a scheme for readout and initialization in a single quantum dot.

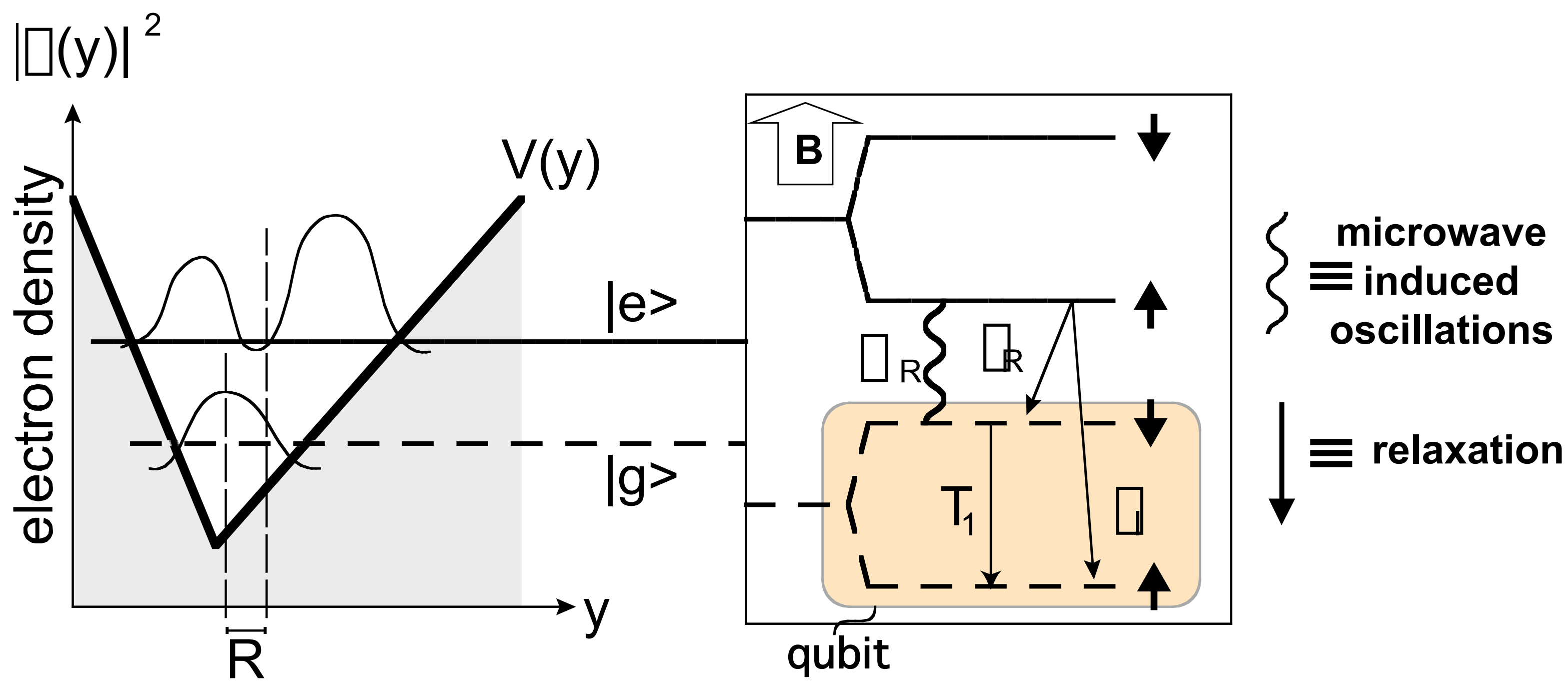




Charge movement in asymmetric well

Gate potentials define quantum well

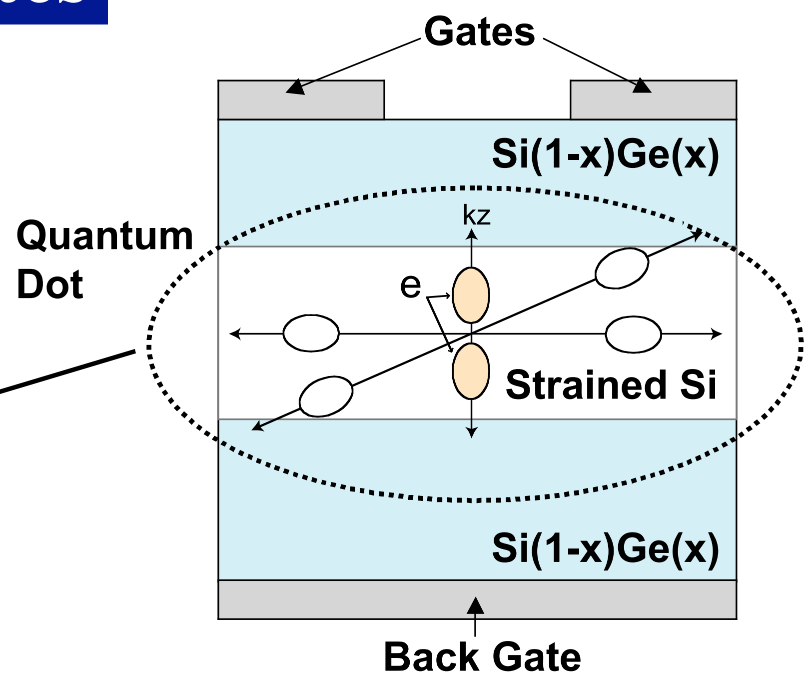
- spin info to charge info via spin-dependent excitation

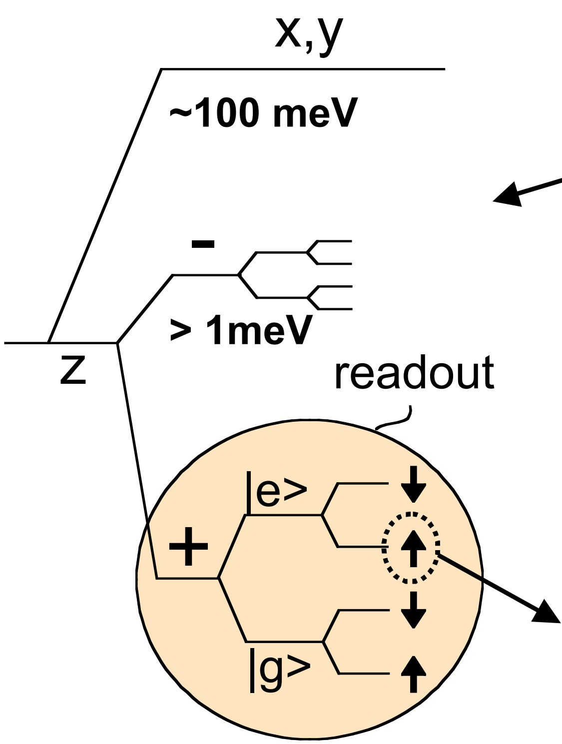


Center of charge movement

$$E_R = E_{e\uparrow} - E_{g\downarrow}$$

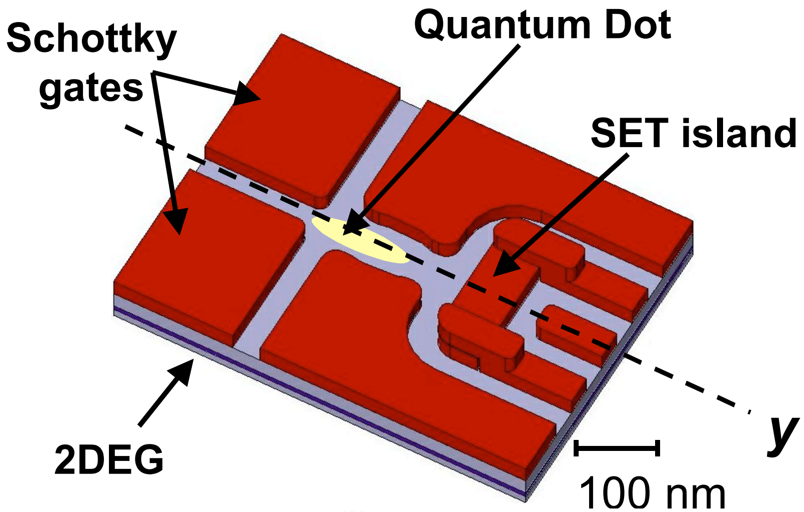
2DEG QD energy states

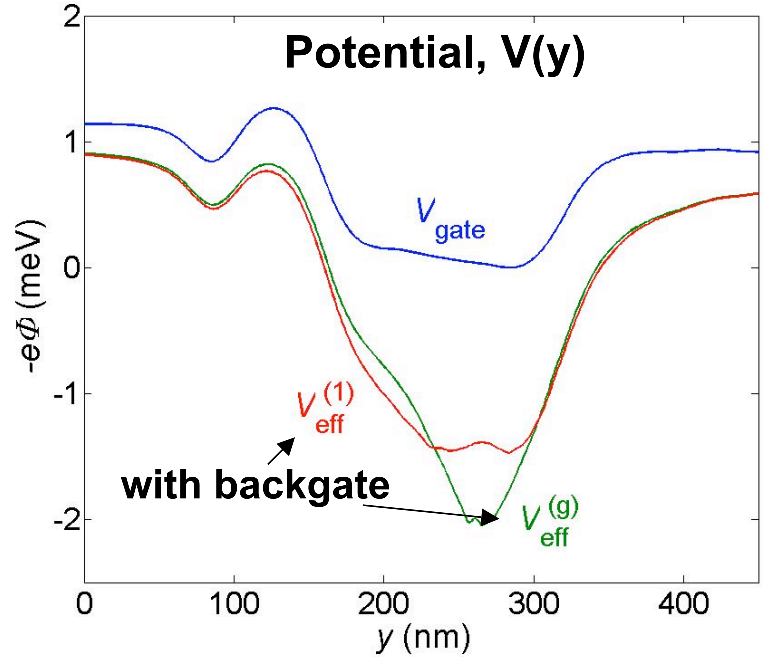


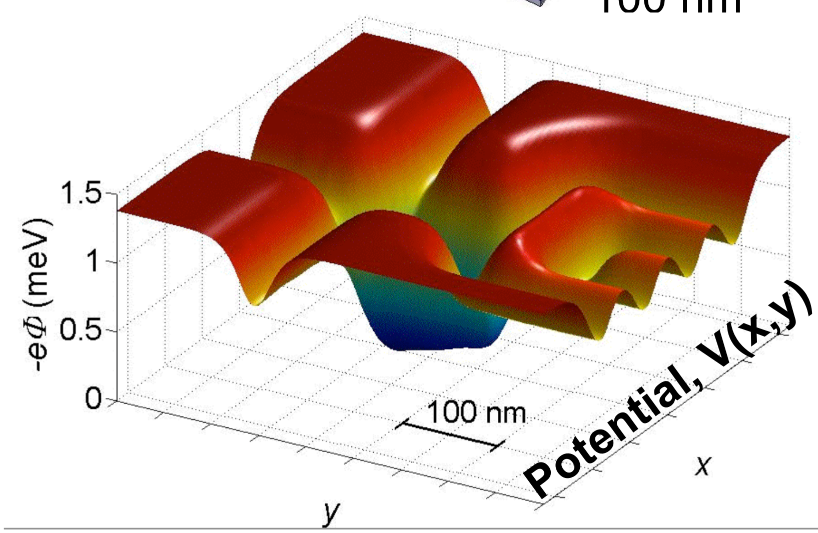


$$|e,\uparrow\rangle = \text{Envelope} \,\square\, \text{Bloch}$$

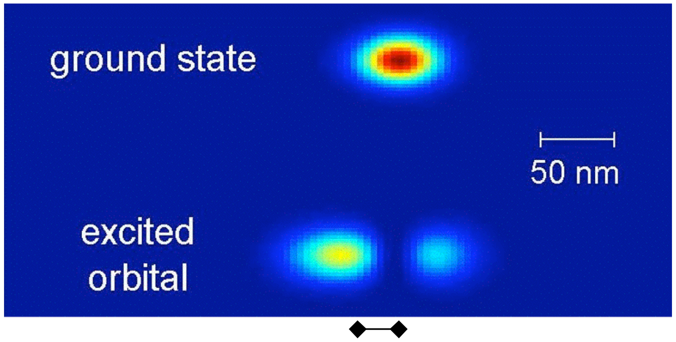
Device Simulation







Wavefunction, |(x,y)|^2

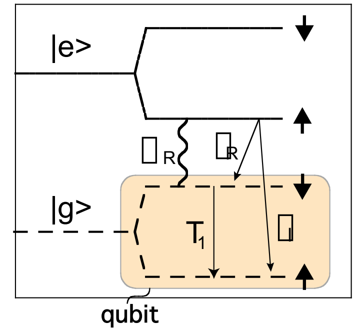


Charge movement ~ 10 nm

Readout

Oscillation Frequency

$$\Box_R = \frac{1}{\hbar}\left|\langle e,\uparrow | V_{\text{LIGHT}} | g,\Box \rangle\right| = M \Box_{\uparrow\uparrow = \Box\Box}$$



dipole approx.

$$\sim \langle e,\uparrow | \mathbf{E}\cdot\mathbf{p} | g,\Box \rangle$$

$$M < 1$$

Mixing Ratio

$$H^{2D}_{\text{SpinOrbit}} = \text{BULK} + \text{RASHBA}$$

Si

$\Box = 8$ m/s

$\Box = 0$

GaAs

$\Box = 1 \Box 40$ m/s

$\Box = 1000 \Box 3000$ m/s

Si **(No external E-field,** $\Box = 8$ m/s **)**

$$M \Box 0.003$$

$$\Box_R \Box 200{,}000\sqrt{Intensity}$$

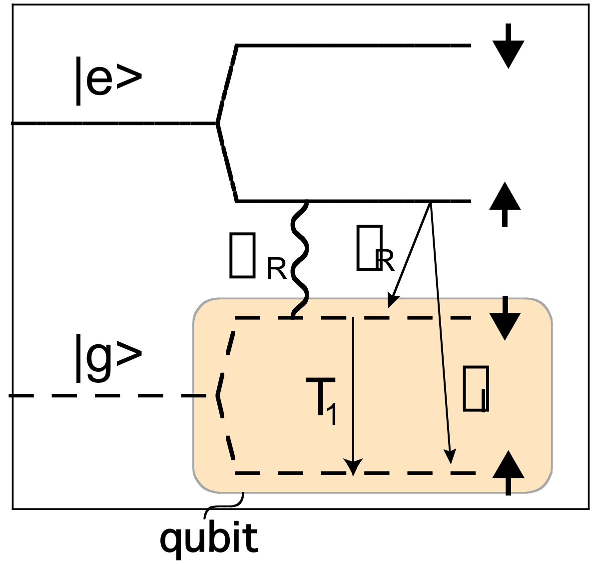
Hz

$0.1 \Box ?\ Watts/m^2$

Electron Relaxation

$$\square_I >> \square_R > 1/T_1$$

→ **Initialization rate dominates**



Si **acoustic phonons**

$$\square_{I=\uparrow\uparrow}(\mathrm{S}i) \square \frac{(E_{31})^5}{6\square\square\hbar^6 v_l^7}(\square_d + \square_u)^2 \left|\langle e,\uparrow|y|g,\uparrow\rangle\right|^2$$

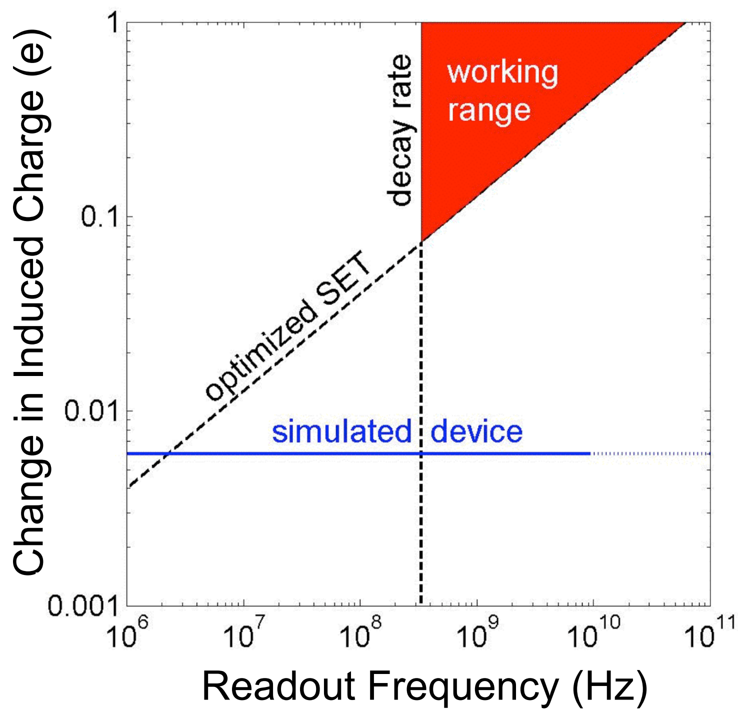
$$1/\square_I \; \square \; 3 \text{ ns}$$

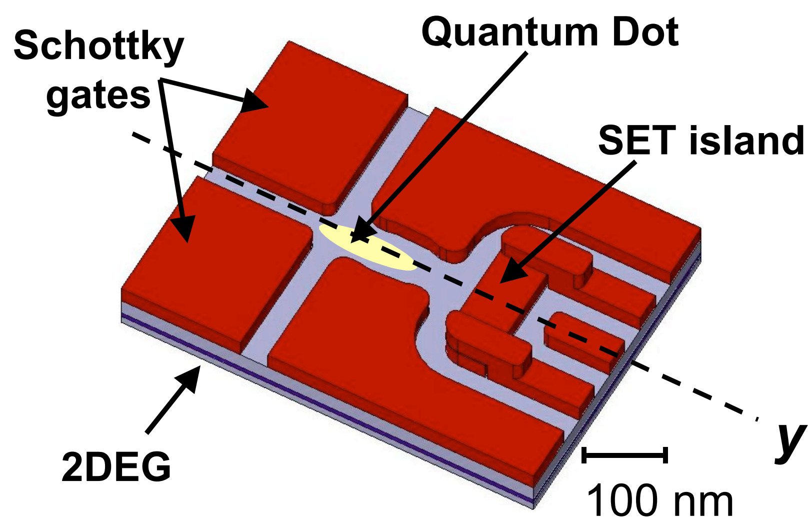
$$E_I(\mathrm{Si}) \square 0.6 \text{ meV}$$

$$T \square 100 \text{ mK}$$

Charge detection

Induced electronic charge on SET island $\Delta q = 0.006e$





Charles Tahan, "Readout and Initialization in a quantum dot" - *March Meeting 2003*

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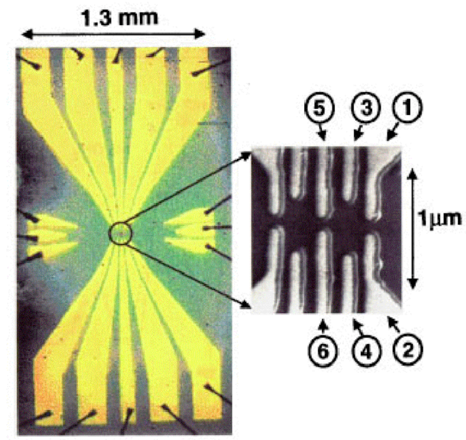
Outlook

Internal antenna

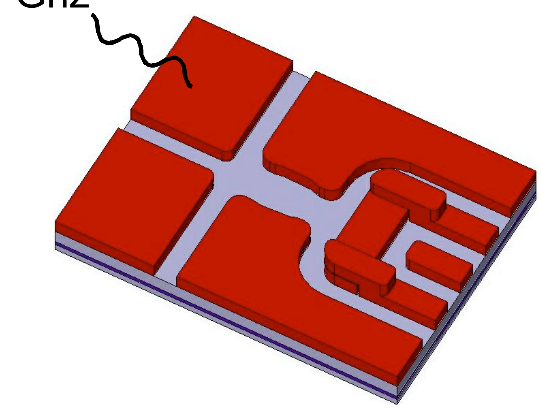
- focus external microwaves to localized region
- increased intensity with less heating



[Blick/van der Weide, APL]

Modulated gates

- Change gate voltage on GHz timescales
- all electric operation



Device Design

- increase spin orbit coupling
- decrease relaxation
- new topologies

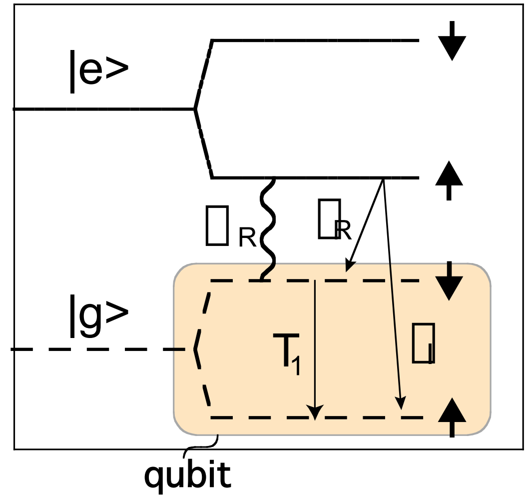
*Readout

Oscillation Frequency

$$\Box_R = \frac{1}{\text{h}} \left| \langle e, \uparrow | V_{\text{LIGHT}} | g, \Box \rangle \right|$$

electric dipole

$$\sim \Box F_{e\uparrow}(\mathbf{r}) [\mathbf{p} \cdot \mathbf{E}(t)] F_{g\Box}(\mathbf{r}) d\mathbf{r}$$



SO Coupling (2D)

$$H_{\text{SO}} = \Box(p_y \Box_y \Box p_x \Box_x) + \Box(p_x \Box_y \Box p_y \Box_x)$$

$$\left| \langle e \uparrow | y | g \Box \rangle \right| \Box \frac{eE_0}{\Box} \left(\Box^2 + \Box^2 \right)^{1/2} \left\langle e \left| y \frac{d}{dy} \right| g \right\rangle$$

GaAs

$\Box = 1 \Box 40$ m/s

$\Box = 1000 \Box 3000$ m/s

Si

$\Box = 8$ m/s

$\Box = 0$

*Numbers

$$E_R = 0.588 \text{ meV}$$

$$\langle e|y|g\rangle = 1.78 \times 10^{-8} \text{ m}$$

$$\langle e|y^2|g\rangle = 9.14 \times 10^{-15} \text{ m}^2$$

$$\langle e|x|g\rangle = 4.12 \times 10^{-10} \text{ m}$$

$$\langle e|x^2|g\rangle = 7.98 \times 10^{-18} \text{ m}^2$$

$$\left\langle e,\uparrow\left| y\frac{d}{dy}\right|g,\downarrow\right\rangle = 6.042$$

$$\left\langle e,\uparrow\left| y\frac{d}{dx}\right|g,\downarrow\right\rangle = 0.45$$

(with $\beta = 8$ m/s)

$$M_{Si} = \frac{\Omega_R}{\Omega_{\uparrow\uparrow=\square\square}} = 0.003$$

$$\Omega_R = M\frac{e}{\hbar}E_0\langle e|y|g\rangle = M\frac{e}{\hbar}\sqrt{\frac{2I}{c\varepsilon_0\sqrt{\varepsilon_{Si}}}}\langle e|y|g\rangle$$

$$= 13{,}346 E_0 = 197{,}642\sqrt{I} \leftarrow Hz$$

$$\Omega_I \approx 330 \times 10^6 Hz$$

$$\frac{\Omega_I}{\Omega_R} \approx \frac{330\times 10^6}{13{,}346 E_0} = \frac{330\times 10^6}{197{,}642\sqrt{I}} = 1 \Rightarrow E_0 = 24726.5 \text{V/m or } I = 1.8\times 10^6 W/m^2$$