Acoustic and Magnetic Traps and Lattices for Electrons in Semiconductors

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Outline

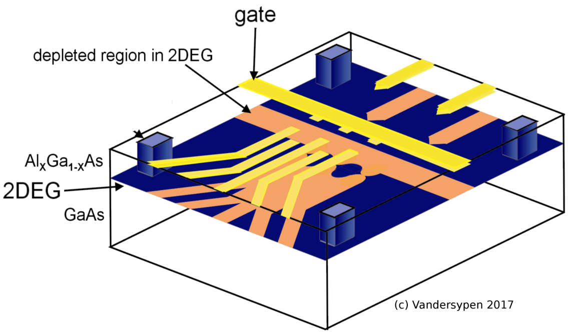
- QIP in semiconductor nanostructures
- quantum-optics inspired proposals to trap and manipulate electrons
- main motivation: analog quantum simulations (e.g., Fermi Hubbard model)
- more generally: find convenient replacement for laser/optical field in the semiconductor setting

The semiconductor approach is closest to conventional IT in materials and fabrication

- based on electronics in semiconductor nanostructures (GaAs, Si, SiGe, ...)
- qubits are small ($\lesssim$100nm), gates are fast ($\sim 0.1 - 10$ns)
- all building-blocks have been demonstrated experimentally, ...
- takes advantage of fabrication technology of semiconductor industry,

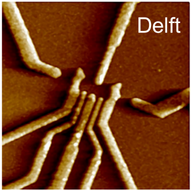
★ main challenges: long-range coupling, uniformity, architecture for scaling beyond 1D geometry

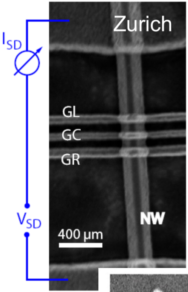
Electrostatically defined quantum dots and spin qubits

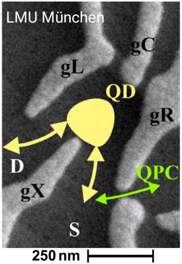


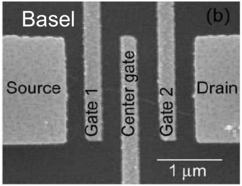
- two-dimensional electron gas (2DEG) at interface; high mobility ($\gtrsim 10^7 \text{cm}^2/\text{Vs}$) and low electron density ($\lesssim 10^3 \mu\text{m}^{-2}$)
- gate electrodes partially deplete 2DEG, non-depleted isolated regions: quantum dots (QD)
- electrical control (number of electrons, tunnel coupling)

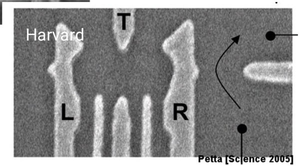
A gallery of quantum dot qubit devices







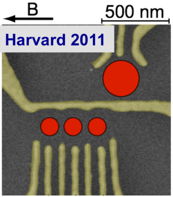


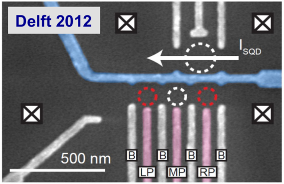


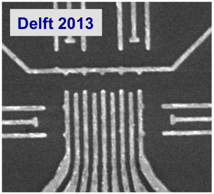
Remarkable progress in the last few years

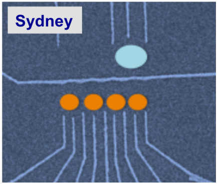
- move to Si structures: much better coherence times > 50ms
- combination with donor spins (Kane proposal): $T_2 > 30$s! [Muhonen 2004]
- new multi-electron spin qubits: fast, all-electrical manipulation, better protected against gate noise [Russ and Burkard 2017]
- gate fidelities $> 99\%$ [Yoneda 2018]
- significant industry involvement (Intel Delft)
- hybrid systems for long-range coupling: QH edge channels, mobile QDs, superconducting striplines [Scarlino 2018], phonon resonators, ...

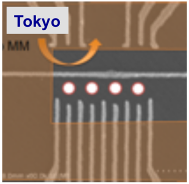
For large-scale quantum computation and quantum simulation we need much larger systems

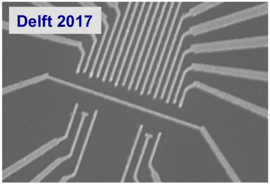




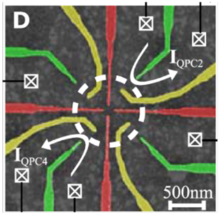




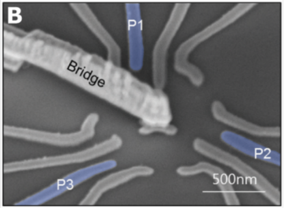




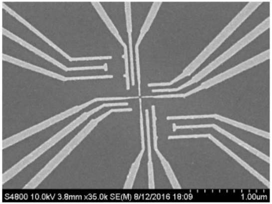
For large-scale quantum computation and quantum simulation we need much larger systems in 2D or 3D



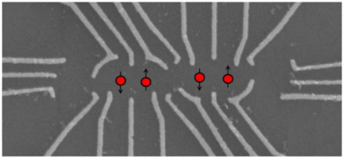
Thalineau et al, APL 2012



Seo et al, PRL 2013



U. Mukhopadhyay, APL 2018



Shulman et al., Science 2012

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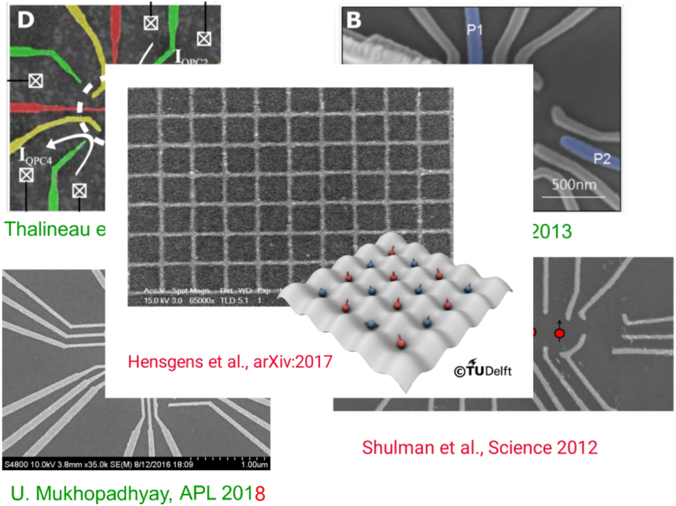


Explore an alternative approach that creates flexible, tunable 2D array of traps

- instead of nano-fabricating many single-particle traps
  can we build an array of many traps at once?

Collaborators on this work

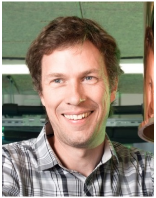
J Knörzer

I Cirac

Harvard U

M Schütz

M Lukin



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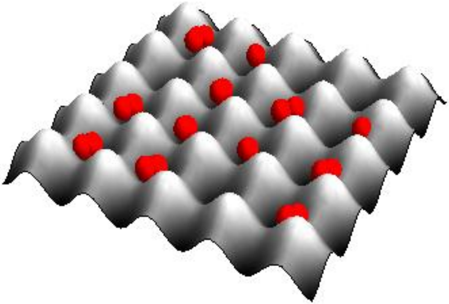
Alternative approach inspired by quantum optics



- optical lattice: standing-wave laser fields can create periodic arrays of traps for atoms
  atoms trapped at intensity minima of the off-resonant light due to optical Stark effect; lattice tunable in situ
- such traps for semiconductor electrons? new parameter regimes for quantum simulation (charged, light, spin-orbit, ...) and adds new (quasi)particles to qsim toolbox

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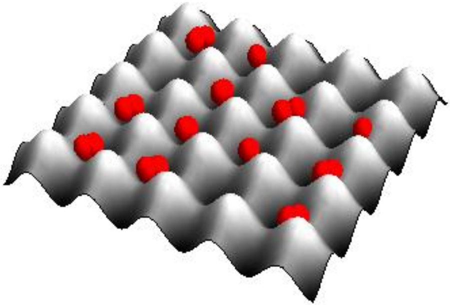

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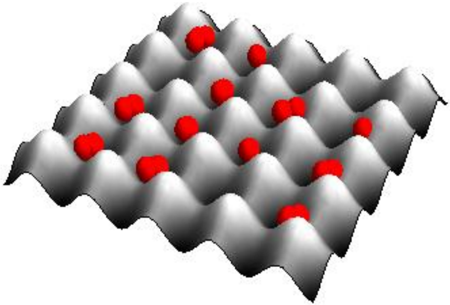

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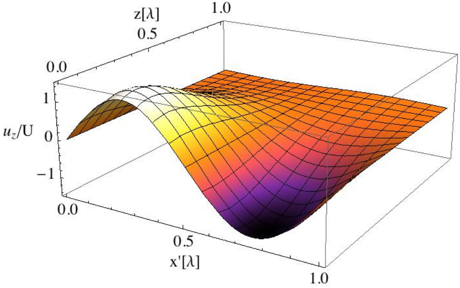
We can obtain a similar structure in a semiconductor quantum well using surface acoustic waves

- surface acoustic waves (SAWs) are mechanical oscillations propagating along the surface of an elastic medium
- they couple to electrons via *strain* and (in piezo-active materials) also by induced *electromagnetic fields*
- properties of SAWs are material-dependent ($\Longrightarrow$ tunable by engineering heterostructures)
- SAWs can also be used to mediate interaction between distant quantum dots and to create moving quantum dots for single electrons ($\rightarrow$ not today's talk...)

Surface Acoustic Waves: Properties

- Rayleigh solution of wave equation at free surface: propagates along surface, decays within wavelength away from surface



frequency	wavelength	speed
$\nu \sim 1 - 20$GHz	$\lambda \sim 0.5 - 10\mu$m	$v_s \sim 3000$m/s

$\Rightarrow$ much slower and smaller than microwave cavities at same ν

$\Rightarrow$ phonon energy $10 - 100\mu$eV, below $k_B T$ @10mK (dilution fridge)

In piezoelectric materials SAWs are accompanied by an oscillating electric field

- piezoelectric effect: mechanical stress changes electric polarization and el. field causes stress

$\Rightarrow$ now coupled wave-equation for strain and electric potential, both of which have Rayleigh form ($v_s \ll c$: quasi-static approx for E)

$\Rightarrow$ use this SAW-generated potential to produce lattice for electrons!

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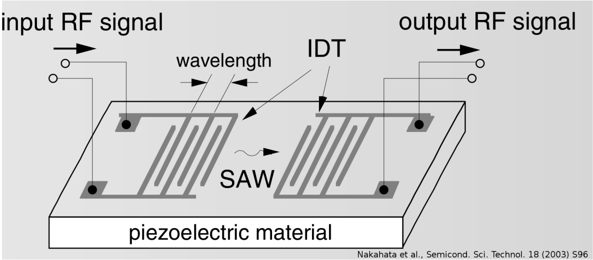
Piezoelectricity has useful consequences

- SAW can be excited electrically by applying voltage pulse to periodic array of surface electrodes (“interdigital transducer”, IDT)



- SAWs can also be detected electrically (via they voltage they induce in IDT)
- SAW can be trapped and guided by surface-patterned structures ($\implies$ SAW resonators, waveguides)

SAWs are already a mature technology

- used as bandpass filters in cell phones, TVs, for measurement and manipulation in biology, material science,...
- used in the quantum information context to
  - transport single electrons between quantum dots
  - trap excitons in a *moving* lattice
  - strong coupling of superconducting qubit to SAW resonator
- promising applications proposed for “quantum acoustics”:
  - to mediate interaction between different qubits (in SAW resonator or waveguide; Schuetz 2015; Wang 2018)
  - SAW-based quantum computing (spin qubits in SAW-defined moving QDs; Barnes 2000)

here: show how to generate 2D periodic potential for electrons in semiconductor quantum well

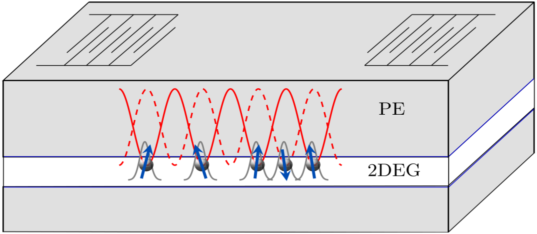
Acoustic Lattices: Outline

1. how to obtain stationary trap from rapidly oscillating potential?
2. stability against heating and losses?

$\Rightarrow$ stability conditions and material requirements

3. potential for quantum simulation?
4. related work on *moving* acoustic lattices: Santos group (PDI Berlin, exciton experiments since 2003); Byrnes *et al.*, PRL 2007.

General Idea of the Acoustic Lattice



- excite standing SAW in piezoelectric heterostructure
- electrons in 2DEG experience time-dependent electric field

⇒ rapidly oscillating force (∼GHz)

- electrons effectively trapped at field nodes since they cannot follow the rapid oscillation

⇒ effective stationary periodic potential!

Trapping of electron in a periodic potential: classical analysis

- a single electron in quantum well sees SAW-induced periodic potential:

$$V(x,t) = V_{\mathrm{SAW}} \cos(kx) \cos(\omega t)$$

⇒ classical equation of motion ($\tilde{x} = kx$):

$$\frac{d^2\tilde{x}}{d\tau^2} = 2\frac{V_{\mathrm{SAW}}}{m(\omega/k)^2/2} \sin(\tilde{x}) \cos(2\tau) = 0$$

- $E_s \equiv \frac{1}{2} m v_s^2$ and $q \equiv \frac{V_{\mathrm{SAW}}}{E_s}$
- Lamb-Dicke regime $\tilde{x} \ll 1$: Mathieu equation

$$\frac{d^2\tilde{x}}{d\tau^2} = 2q \cos(2\tau)\tilde{x} = 0$$

⇒ stability regions: e.g., $0 < q \lesssim 0.91$: slow, harmonic secular motion and fast, low-amplitude micro-motion (cf. trapped ions)

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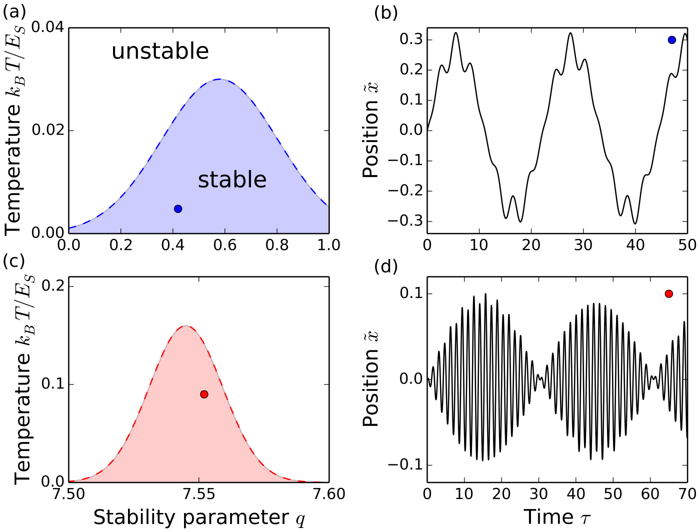
Two timescales: secular motion and micromotion



Separation of timescales can be exploited in quantum mechanical Floquet analysis

- periodic Hamiltonian ($H_S(t + 2\pi/\omega) = H_S(t)$):

$$H_S(t) = \frac{\hat{p}^2}{2m} + V_{\mathrm{SAW}} \cos(\omega t) \cos(k\hat{x})$$

- Floquet theory: Schrödinger equation with periodic $H(t)$

$$i\hbar \frac{\partial}{\partial t} \Psi(x,t) = H_S(t)\Psi(x,t)$$

has solutions

$$\Psi_\nu(x,t) = e^{-i\nu t/\hbar} u_\nu(x,t),$$

with periodic $u_\nu(x, t + 2\pi/\omega) = u_\nu(x,t)$; quasi-energy $\hbar\nu$

$\Rightarrow$ for large ω: separation of timescales: slow ν, fast ω

We can construct a time-dependent basis transformation so that H_S becomes time-independent

- apply unitary basis transformation e^{-iF} (F hermitian and periodic)
- such that Schrödinger equation for $\Phi = e^{iF}\Psi$ is time-*independent*:

$$i\hbar \frac{\partial}{\partial t}\Phi(x,t) = G\Phi(x,t)$$

- the effective time-independent Hamiltonian G is

$$G = e^{iF} H_S(t) e^{-iF} + i\hbar \frac{\partial e^{iF}}{\partial t} e^{-iF}$$

- for large ω: obtain G, F explicitly as power series in ω^{-1}

The leading term of the effective Hamiltonian yields a stationary periodic lattice potential

- make *ansatz* $G = G_0 + \sum_n \left(\frac{1}{\omega}\right)^n G_n$ and $F = \sum_n \left(\frac{1}{\omega}\right)^n F_n$
- then we find to 2nd order

$$G_0 + G_2 \equiv H_{\text{eff}} = \frac{\hat{p}^2}{2m} + V_0 \sin^2(k\hat{x})$$

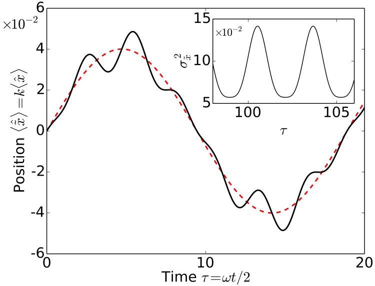
  with $V_0 = \frac{1}{8} q^2 E_S$ (again: large $E_S \implies$ deep potential!)
- higher-order terms can be computed systematically; they are negligible for large ω

For small x, the particle experiences a *harmonic potential* at $x = 0$

harmonic approximation ($kx \ll 1$):

$$H_{\text{eff}} \approx \frac{\hat{p}^2}{2m} + \frac{1}{2} m \omega_0^2 \hat{x}^2$$

$\omega_0 = q\omega/\sqrt{8}$ secular frequency, "trap frequency" ($\ll \omega$)



All the above considerations characterize the working conditions of our scheme

- chain of collectively sufficient conditions for a good lattice:

⇒ we can't just drive harder, since that moves $q = V_{\rm SAW}/E_S$ out of stability region; nor just faster (since then we lose the bound states)

- some typical numbers: $\hbar\gamma \sim 0.1\mu$eV (spont emission rate of acoustic phonons); readily compatible with $T = 10 - 100$mK ($k_B T = 1 - 10\mu$eV); SAW frequency $\omega/2\pi = 25$GHz: $\hbar\omega = 100\mu\text{eV} \implies \hbar\omega_0 \lesssim 20\mu\text{eV}$

⇒ all works out for $E_S \gg 100\mu$**eV!**

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thermally stable trap, motional ground state approachable

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separation secular / micromotion time scales ($q \sim \omega_0/\omega \ll 1$)

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There are a number of promising materials / heterostructures to realize acoustic lattices

setup	m/m_0	$v_s[\mathrm{km/s}]$	$E_S[\mu\mathrm{eV}]$
electrons in GaAs*	0.067	~ 3	~ 1.7
heavy holes in GaAs**	0.45	$\sim (12-18)$	$\sim 184-415$
electrons in Si**	0.2	$\sim (12-18)$	$\sim 82-184$
holes in GaN**	1.1	$\sim (12-18)$	$\sim 450-1010$
electrons in $\mathrm{MoS_2}$**	0.67	$\sim (12-18)$	$\sim 274-617$
trions in $\mathrm{MoS_2}$**	1.9	$\sim (12-18)$	$\sim 794-1787$

Table : Estimates for the energy scale E_S for different physical setups. ** refer to relatively fast values of v_s in (diamond-boosted) heterostructures featuring high-frequency SAW and PSAW modes [Benetti *et al.*, APL (2005), Glushkov *et al.* 2012].

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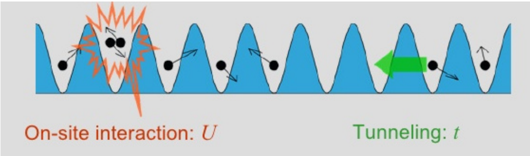
Application: simulation of Fermi-Hubbard model



$$H_{\rm FH} = -t \sum_{\langle i,j\rangle,\sigma} (c^\dagger_{i,\sigma} c_{j,\sigma} + {\rm h.c.}) + \sum_{i,\sigma} \mu_i n_i + \sum_{\sigma,\sigma'} \sum_{ijkl} U_{ijkl} c^\dagger_{i,\sigma'} c^\dagger_{j,\sigma} c_{k,\sigma} c_{l,\sigma'},$$

- we estimate $t/E_S \approx 3 \times 10^{-3}$; unscreened $U \gg t, \omega_0$
  $\Longrightarrow$ need screening layer at distance $d \sim 0.3a$
- case study holes in GaN quantum well on AlN/diamond

$\hbar\omega$	$q = V_{\rm SAW}/E_S$	$\hbar\omega_0$	V_0	$n_b = V_0/\omega_0$	$\lambda/2$[nm]	d[nm]	t	U	$k_B T$
207	0.5 - 0.7	37-51	31-61	0.85-1.2	180	10-100	0.7-1.8	5-270	1-10

Table : Energy scales (in μeV) for an exemplary setup with $E_S = 1\text{meV}$ and $f = 50\text{GHz}$.

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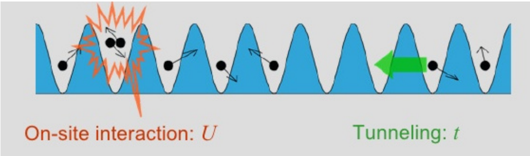

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Magnetic Lattices can avoid micromotion

- two trapping paradigms in quantum optics:
  ponderomotive trap: time-dependent quadrupole electric field, charged particle trapped at $\mathbf{r}_0$ where $\mathbf{E}(\mathbf{r}_0) = 0$
  dipole trap: off-resonant standing-wave laser field induces position-dependent AC Stark shift, effective potential minima at maxima (or minima) of the intensity.

⇒ no micromotion and associated stability issues in dipole traps

? can we trap this way using the acoustic toolbox?

- yes, we can: drive transition between the two spin states in a static *B* field

A different trapping mechanism: magnetic lattices

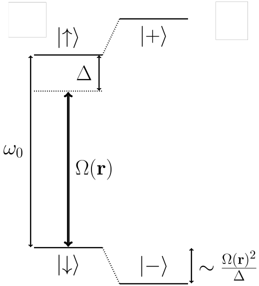
collaboration with H. Hübl, M. Weiler
Walther-Meissner-Institut / TU München

- magnetostrictive or ferromagnetic layer endows SAW with oscillating magnetic component at 2DEG

- oscillating B field drives transition b/w spin states

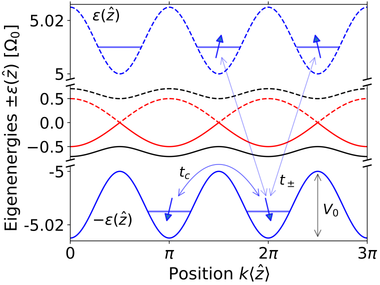
$$H = \frac{p_z^2}{2m} + \frac{\omega + \Delta}{2}\sigma^z + \frac{\Omega_0}{2}\cos(kz)\cos(\omega t)\sigma^x$$

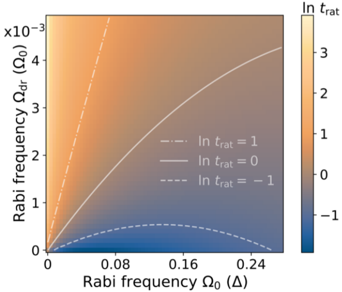
- off-resonant driving $\implies$ position-dependent AC-Stark shifts for the two Zeeman eigenstates



Spin-dependent lattices

$\Rightarrow$ two effective periodic potentials, one for each spin orientation:



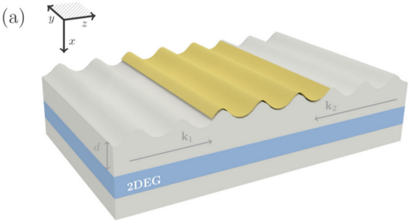


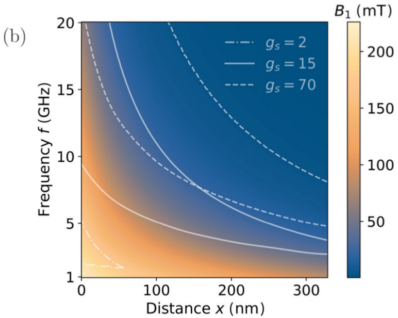
$\Rightarrow$ effective periodic spin-dependent potential (Fig.: $\Delta/\Omega_0 = 10, 1, 0$)

$$H = \frac{p_z^2}{2m} + \epsilon(z)\sigma^z; \quad \left(\epsilon(z) \approx |\Delta|/2 + \frac{\Omega_0^2}{4|\Delta|}\right)$$

- spin-conserving hopping: t_c; spin-flip-hopping $t_\pm$ (assisted by resonant drive): wide range of ratios $t_c/t_\pm$ can be tuned

Reachable magnetic field strengths





- reachable inhomogeneous *B* field depends on driving frequency and distance from ferromag layer
  the larger *g* factor, the broader (and more favorable) the stable region for magnetic lattice

Material requirements for magnetic lattice

- position-dependent spin-groundstate: kinetic term can induce transition between internal states
- avoided in *adiabatic limit* $\omega_{\mathrm{HO}} \ll |\Delta|$
- stability conditions:

$$\gamma, k_B T \ll \omega_{\mathrm{HO}} \lesssim V_{\mathrm{trap}} \lesssim \Omega_0 \lesssim \omega$$

(low losses, ground-state cooling; adiabaticity, trapped states, ...)

$\Rightarrow$ the larger Ω_0 (and ω), the better: use large *g* factors, high magnetization, strong SAW amplitude, high-frequency SAWs

$\Rightarrow$ traps with depth $10 - 100\mu$eV $\gg k_B T$ are feasible

Spin-dependent Fermi-Hubbard lattice

- Hubbard lattices for two spin directions shifted with respect to each other, two spin-directions Zeeman split

⇒ nearest-neighbor hopping requires (off-resonant) spin-flip, weak driving fields allows to independently tune nearest-neighbor $t_{\text{spin-flip}}$ and make it equal to the largest spin-conserving tunneling term

- combining magnetic and piezoelectric materials allows to combine both trapping mechanisms: traps add constructively for one spin orientation, and partially cancel for the other (yield complicated stability diagram)

Summary

- SAWs as a versatile tool in semiconductor QIP
- SAWs endowed with electric or magnetic fields can be used to create standing-wave acoustic lattices, tunable in-situ
- conditions for trapping of electrons $\Rightarrow$ possible material platforms
- simulating Fermi-Hubbard-type Hamiltonians appears feasible
- but more work (readout? phase transitions? best materials?) needs to be done; experiments needed!
- there are very strong alternative approaches (QD arrays, lattice for electron constructed atom-by-atom (with STM on metal surfaces))

More generally, SAW are a promising system to manipulate, couple, and measure solid-state qubits

- clean and versatile on-chip method to access many different qubits (QDs, NV, trapped ions, transmons,...)
- can play role like laser-/cavity-/waveguide modes in cavity-QED
- SAW properties tunable by heterostructure materials
- classical SAW fields to trap, move, measure qubits
  - reliable electron qubit transport over sample-size distances
  - acoustic lattices for electrons or holes in quantum wells
- SAW modes in quantum regime (SAW resonator):
  - high cooperativities: interconversion of spin-qubits and phonons; mediate interactions between different qubits

Outlook: many open questions and possibilities

- **quantum acoustics:**
  - more flexible, scalable architectures using SAW-induced moving qubits and SAW-modes as quantum bus?
  - hybrid structures (QDs, superconducting circuits, NV centers)
  - non-classical phonon fields, resonator-QAD
- **acoustic and magnetic lattices:**
  - heterostructures to engineer SAW and particle properties
  - improve lattice (material, driving, trapping mechanism)
  - explore new parameter regimes of Hubbard model
  - lattice for other quasiparticles: electrons with atypical dispersion, spin-orbit coupling, excitons, ...
  - new playground for quantum simulation
- **mobile quantum dots:**
  - tool for long-range coupling, read/write head
  - fermionic quantum channel: on-chip q communication

Thanks to my co-workers

MPQ

J Knörzer

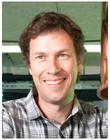
I Cirac

Harvard U

M Schütz

M Lukin

TU Delft



L Vandersypen

Schuetz *et al.*, Phys. Rev. X **5** 031031 (2015); arXiv:1504.05127

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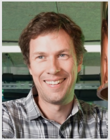

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