Quantum Acoustics and Acoustic Traps and Lattices for Electrons in Semiconductors

Géza Giedke

Ikerbasque Foundation and Donostia International Physics Center

September 14, 2017

Advanced School and Workshop on

Quantum Science and Quantum Technologies

ICTP Trieste

Collaborators on this work

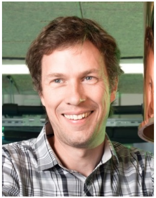
J Knörzer

I Cirac

Harvard U

M Schütz

M Lukin



L Vandersypen

Surface Acoustic Waves for QIP

- bosonic fields/modes play crucial role in almost all QIP implementations (trapped ions, all photonic/quantum optical approaches, circuit-QED, ...)
- QIP in semiconductor nanostructures: still no “canonical” choice
- recent success using surface acoustic phonons for
  - electron transport (C Ford (Oxford), T Meunier (Grenoble): phys stat sol (b) **254** (2017): Ford, arXiv:1702.06628 [3] and Hermelin *et al.* [8])
  - trapping exciton-polaritons with SAWs: P Santos (PDI Berlin): de Lima & Santos, Rep Prog Phys **68** (2005).
  - SAW-based quantum computing: Barnes *et al.*, PRB **62** (2000) [1].
  - related: SAW-resonators and superconducting qubits: P Delsing (Chalmers): Gustafsson, Science **346** (2014) [7].
- aim of this talk: SAWs modes as **quantum bus** and SA standing waves for **acoustic lattices** for electrons

Surface Acoustic Waves for QIP

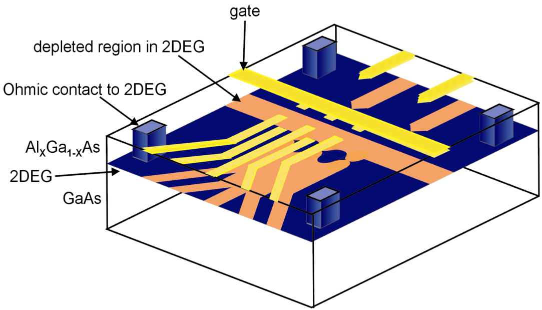
- bosonic fields/modes play crucial role in almost all QIP implementations (trapped ions, all photonic/quantum optical approaches, circuit-QED, ...)
- QIP in semiconductor nanostructures: still no "canonical" choice
- recent success using surface acoustic phonons for
  - electron transport (C Ford (Oxford), T Meunier (Grenoble): phys stat sol (b) **254** (2017): Ford, arXiv:1702.06628 [3] and Hermelin *et al.* [8])
  - trapping exciton-polaritons with SAWs: P Santos (PDI Berlin): de Lima & Santos, Rep Prog Phys **68** (2005).
  - SAW-based quantum computing: Barnes *et al.*, PRB **62** (2000) [1].
  - related: SAW-resonators and superconducting qubits: P Delsing (Chalmers): Gustafsson, Science **346** (2014) [7].
- aim of this talk: SAWs modes as **quantum bus** and SA standing waves for **acoustic lattices** for electrons

Surface Acoustic Waves for QIP

- bosonic fields/modes play crucial role in almost all QIP implementations (trapped ions, all photonic/quantum optical approaches, circuit-QED, ...)
- QIP in semiconductor nanostructures: still no “canonical” choice
- recent success using surface acoustic phonons for
  - electron transport (C Ford (Oxford), T Meunier (Grenoble): phys stat sol (b) **254** (2017): Ford, arXiv:1702.06628 [3] and Hermelin *et al.* [8])
  - trapping exciton-polaritons with SAWs: P Santos (PDI Berlin): de Lima & Santos, Rep Prog Phys **68** (2005).
  - SAW-based quantum computing: Barnes *et al.*, PRB **62** (2000) [1].
  - related: SAW-resonators and superconducting qubits: P Delsing (Chalmers): Gustafsson, Science **346** (2014) [7].
- aim of this talk: SAWs modes as **quantum bus** and SA standing waves for **acoustic lattices** for electrons

Reminder: Quantum-dot Spin-qubits (cf. talk D Loss)

Electrostatically defined quantum dots



- Electrically measured (contact to 2DEG)
- Electrically controlled number of electrons
- Electrically controlled tunnel barriers

Reminder: Quantum-dot Spin-qubits (cf. talk D Loss)

- proposed by Loss & DiVincenzo, PRA **57** (1998); cond-mat/9701055 [12]
- qubit: spin of electron in QD

✓ very compact, fast gates
($10^4 - 10^6$ operations within $T_{2,DD}$ (GaAs vs Si))

✓ few-qubit demonstrations

? long-range coupling?

? architecture beyond 1d arrays?

★ can SAWs help?

Reminder: Quantum-dot Spin-qubits (cf. talk D Loss)

- proposed by Loss & DiVincenzo, PRA **57** (1998); cond-mat/9701055 [12]
- qubit: spin of electron in QD

✓ very compact, fast gates ($10^4 - 10^6$ operations within $T_{2,DD}$ (GaAs vs Si))

✓ few-qubit demonstrations

? long-range coupling?

? architecture beyond 1d arrays?

★ can SAWs help?

Reminder: Quantum-dot Spin-qubits (cf. talk D Loss)

- proposed by Loss & DiVincenzo, PRA **57** (1998); cond-mat/9701055 [12]
- qubit: spin of electron in QD

✓ very compact, fast gates ($10^4 - 10^6$ operations within $T_{2,DD}$ (GaAs vs Si))

✓ few-qubit demonstrations

? long-range coupling?

? architecture beyond 1d arrays?

★ can SAWs help?

Outline

1. what are surface acoustic waves...
2. ... and what may they be useful for?
3. “cavity-QED” with SAWs
4. acoustic lattices for electrons
5. summary and outlook

Surface Acoustic Waves

- phonons present in any elastic medium, propagate within substrate
- surface phonons naturally confined to within λ of surface
  - $\Rightarrow$ small mode-volume
  - $\Rightarrow$ trapped/guided by surface patterning
- can be augmented with electromagnetic component using piezoelectric (GaAs, ZnO) or magnetostrictive (terfenol-D) material

Applications of SAWs

- can play the roles of optical fields and modes in the solid-state setting:
- electron transport (= optical tweezer)
- phonon-driven quantum gates (= laser-driven gates)
- acoustic lattices (= optical lattices)
- SAW resonators and waveguides as quantum bus (= cavity-QED)

Surface Acoustic Waves

- mechanical waves propagating at surface: Hooke's law and coupling to electric potential ϕ in piezoelectric materials: coupled mechanical-electrical oscillations

$$\begin{aligned}\rho \ddot{u}_i &= c_{ijkl}\frac{\partial^2 u_k}{\partial x_j \partial x_l} + e_{kij}\frac{\partial^2 \phi}{\partial x_j \partial x_k} \\ e_{ijk}\frac{\partial^2 u_j}{\partial x_i \partial x_k} - \epsilon_{ij}\frac{\partial^2 \phi}{\partial x_i \partial x_j} &= 0, \quad z > 0 \\ \triangle \phi &= 0, \quad z < 0\end{aligned}$$

with stress-free surface boundary condition

$$c_{i\hat{z}kl}\frac{\partial u_k}{\partial x_l} = 0 + e_{ki\hat{z}}\frac{\partial \phi}{\partial x_k} \quad \text{at } z = 0$$

and continuity of $\perp$ component of electric displacement at $z = 0$

$\Rightarrow$ electrical excitation and detection: interdigital transducer (IDT):

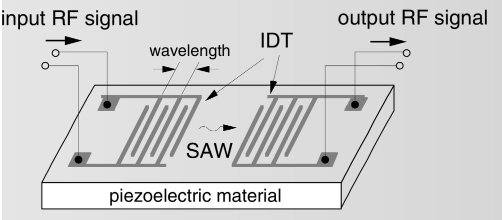
- can be trapped and guided by surface-patterned structures:
- high-Q SAW resonators: $Q = 10^4 - 10^5$ [Phys. Rev. B **93** (2016);

Surface Acoustic Waves

- mechanical waves propagating at surface: Hooke's law and coupling to electric potential ϕ in piezoelectric materials: coupled mechanical-electrical oscillations with stress-free surface boundary condition

⇒ electrical excitation and detection: interdigital transducer (IDT):

- can be trapped and guided by surface-patterned structures:
- high-Q SAW resonators: $Q = 10^4 - 10^5$ [Phys. Rev. B **93** (2016); arXiv:1510.04965 [13]]
- and SAW wave-guides

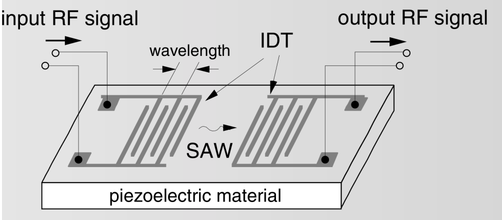


Surface Acoustic Waves

- mechanical waves propagating at surface: Hooke's law and coupling to electric potential ϕ in piezoelectric materials: coupled mechanical-electrical oscillations with stress-free surface boundary condition

$\Rightarrow$ electrical excitation and detection: interdigital transducer (IDT):

- can be trapped and guided by surface-patterned structures:
- high-Q SAW resonators: $Q = 10^4 - 10^5$ [Phys. Rev. B **93** (2016); arXiv:1510.04965 [13]]
- and SAW wave-guides

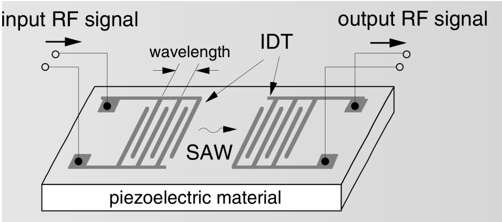


Surface Acoustic Waves

- mechanical waves propagating at surface: Hooke's law and coupling to electric potential ϕ in piezoelectric materials: coupled mechanical-electrical oscillations with stress-free surface boundary condition

$\Rightarrow$ electrical excitation and detection: interdigital transducer (IDT):

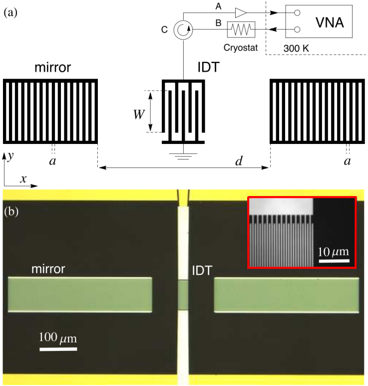
- can be trapped and guided by surface-patterned structures:
- high-Q SAW resonators: $Q = 10^4 - 10^5$ [Phys. Rev. B **93** (2016); arXiv:1510.04965 [13]]
- and SAW wave-guides



High-Q SAW-Resonators: $Q = 10^4 - 10^5$

Surface acoustic wave resonators in the quantum regime

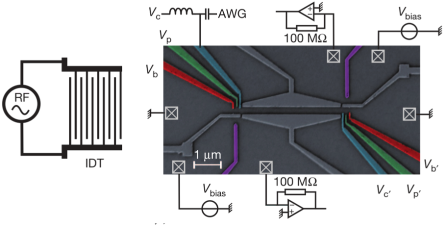
R. Manenti, M. J. Peterer, A. Nersisyan, E. B. Magnusson, A. Patterson, and P. J. Leek*
Clarendon Laboratory, Department of Physics, University of Oxford, OX1 3PU, Oxford, United Kingdom
(Dated: October 19, 2015)



Classical SAWs: Moving Quantum Dots

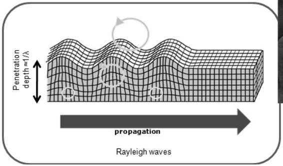
Electrons surfing on a sound wave as a platform for quantum optics with flying electrons

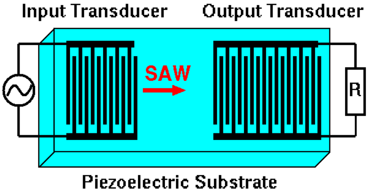
Sylvain Hermelin[1], Shintaro Takada[2], Michihisa Yamamoto[2,3], Seigo Tarucha[2,4], Andreas D. Wieck[5], Laurent Saminadayar[1,6], Christopher Bäuerle[1] & Tristan Meunier[1]



- proposal for quantum computing based on moving QDs [Barnes et al., 2000 [1]]

Surface Acoustic Waves: Properties





- propagate along surface, combine longitudinal and transverse motions, decay within λ away from surface
- weak coupling to bulk waves (not phase matched)
- frequencies: $\nu \sim 1 - 20$GHz

$\Rightarrow$ energies $\sim 10 - 100\mu\mathrm{eV}$ ($\approx$ ground state @ 10mK (dilution fridge))

- speed $v_s \sim 3000$m/s
- wavelength $\lambda \sim 0.5 - 10\mu$m

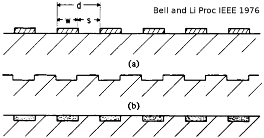
$\Rightarrow$ much smaller than microwave cavities at same frequency

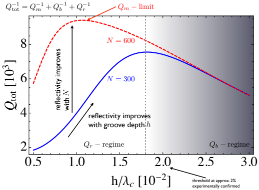
Promising for cavity-"QAD": SAW Resonators

- high-Q SAW resonators demonstrated ("mirrors" periodic arrays of electrodes or grooves; typically several 100)
- loss mechanisms: diffraction losses (finite width of reflectors), coupling to bulk modes, leakage loss through reflectors, propagation loss

$\Rightarrow$ trade-offs: small mode volume $\Longrightarrow$ deep groves $\Longrightarrow$ strong bulk losses

$\Rightarrow$ for $\lambda = 1\mu$m, quality factors $Q = 10 - 10^5$ achievable (for length $\sim 1 - 100\mu$m)





SAWs as a universal quantum transducer

- aim: show that a variety of “standard” qubits can couple strongly to SAW cavity...

$\Rightarrow$ Jaynes-Cummings dynamics

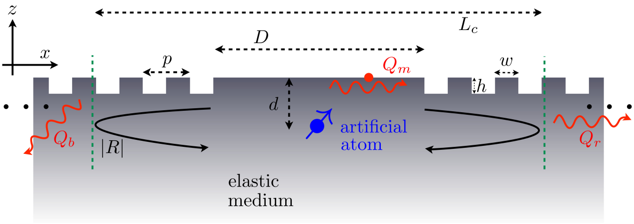
$\Rightarrow$ on-chip long-range coupling of qubits

$\Rightarrow$ interconversion of QI between different qubits (hybrid systems)

$\Rightarrow$ prospects to have the toolbox of cavity-QED available

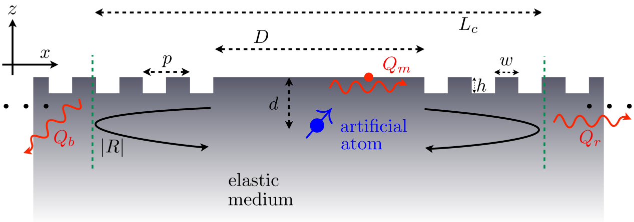
★ prototypical example: state-transfer protocol between two cavities

SAW Quantum Transducer



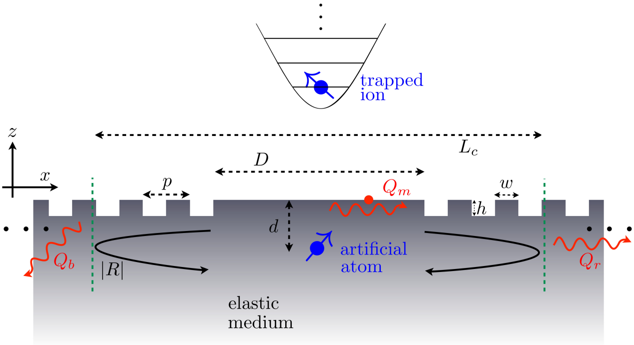
- couple resonator SAW-mode to artificial atom (QD, NV,...)

SAW Quantum Transducer



- couple resonator SAW-mode to artificial atom (QD, NV,...)
- use cavity output Q_r as quantum bus to 2nd node

SAW Quantum Transducer



- couple resonator SAW-mode to artificial atom (QD, NV,...)
- SAW field extends above surface: can also couple to qubits there

Single-phonon coupling strength and cooperativity

? which systems provide good conditions for SAW transducers?

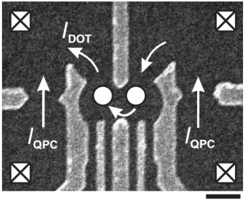
- central quantity cooperativity $C = g^2 T_2 Q / [\omega_c (n_{\mathrm{th}} + 1)]$
  $C > 1$: coherent coupling stronger than losses
  can show fidelity of state transfer $F \approx 1 - \epsilon - \frac{1}{C}$

	charge qubit (DQD)	spin qubit (DQD)	trapped ion	NV-center
g	$(200 - 450)\mathrm{MHz}$	$(10 - 22.4)\mathrm{MHz}$	$(1.8 - 4.0)\mathrm{kHz}$	$(45 - 101)\mathrm{kHz}$
C	$11 - 55$	$21 - 106$	$7 - 36$	$10 - 54$

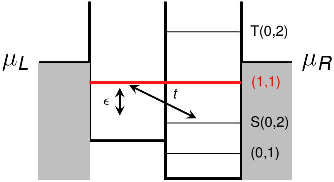
★ $C > 10$ possible in all these systems (q gates, q state transfer, ...)

Example: Spin Qubit in Double Quantum Dot

- double QD (DQD), Coulomb blockade: (1,1) regime



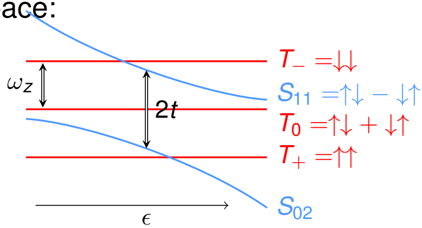
[Hanson 2007]



- Hamiltonian within (1,1)-(0,2) subspace:

$$H_{\text{el}} = \omega_Z(S_L^z + S_R^z) - \epsilon|S_{02}\rangle\langle S_{02}| \\ + t\left(|S_{11}\rangle\langle S_{02}| + \text{h.c.}\right) - \Delta(|T_0\rangle\langle S_{11}| + \text{h.c.})$$

most advanced QD qubit: two-electron singlet-triplet qubit: span$\{|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle, |S_{02}\rangle\}$; all-electrical manipulation, coupling, and readout [Shulman et al. Science 2012 [17]]

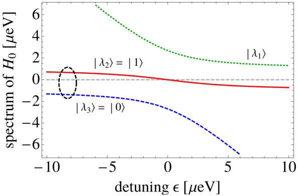


Coupling SAWs and Quantum Dots

- $\lambda_{\rm SAW} \gg$ size of DQD: add term $H_{\rm SAW} = \sum V_{\rm SAW}(x_i) n_i$ to $H_{\rm DQD}$
- detuning of $|S_{02}\rangle$ varies periodically with $V_{\rm SAW}$:

$$\begin{aligned} H &= \omega_0(|T_-\rangle\langle T_-| - |T_+\rangle\langle T_+|) - \Delta B(|T_0\rangle\langle S_{11}| + \text{h.c.}) \\ &+ t(|S_{02}\rangle\langle S_{11}| + \text{h.c.}) - (\epsilon - \Delta V_{\rm SAW}(t))|S_{02}\rangle\langle S_{02}| \end{aligned}$$

three eigenstates in $S_z = 0$ subspace:
$|\lambda_l\rangle = \alpha_l |T_0\rangle + \beta_l |S_{11}\rangle + \kappa_l |S_{02}\rangle$
choose $\omega_{\rm SAW}$ resonant with $|\lambda_2\rangle \leftrightarrow |\lambda_3\rangle$



$\Rightarrow$ $H_{\rm eff} = \omega_{\rm eff}(|\lambda_2\rangle\langle\lambda_2| - |\lambda_3\rangle\langle\lambda_3|) + \Omega_{\rm eff}(a|\lambda_2\rangle\langle\lambda_3| + \text{h.c.})$

$\Rightarrow$ single-phonon coupling strength $g_{\rm QD} \sim 10 - 20$MHz possible

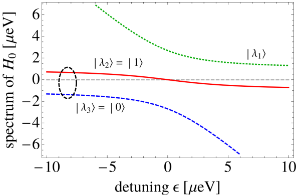
$\Rightarrow$ single spin cooperativity $C = g_{\rm QD}^2 T_2/\kappa \sim 20 - 100$

Coupling SAWs and Quantum Dots

- $\lambda_{\text{SAW}} \gg$ size of DQD: add term $H_{\text{SAW}} = \sum V_{\text{SAW}}(x_i)n_i$ to H_{DQD}
- detuning of $|S_{02}\rangle$ varies periodically with V_{SAW}:

$$\begin{aligned} H &= \omega_0(|T_-\rangle\langle T_-| - |T_+\rangle\langle T_+|) - \Delta B(|T_0\rangle\langle S_{11}| + \text{h.c.}) \\ &+ t(|S_{02}\rangle\langle S_{11}| + \text{h.c.}) - (\epsilon - \Delta V_{\text{SAW}}(t))|S_{02}\rangle\langle S_{02}| \end{aligned}$$

three eigenstates in $S_z = 0$ subspace:
$|\lambda_l\rangle = \alpha_l|T_0\rangle + \beta_l|S_{11}\rangle + \kappa_l|S_{02}\rangle$
choose ω_{SAW} resonant with $|\lambda_2\rangle \leftrightarrow |\lambda_3\rangle$



$\Rightarrow$ $H_{\text{eff}} = \omega_{\text{eff}}(|\lambda_2\rangle\langle\lambda_2| - |\lambda_3\rangle\langle\lambda_3|) + \Omega_{\text{eff}}(a|\lambda_2\rangle\langle\lambda_3| + \text{h.c.})$

$\Rightarrow$ single-phonon coupling strength $g_{\text{QD}} \sim 10 - 20$MHz possible

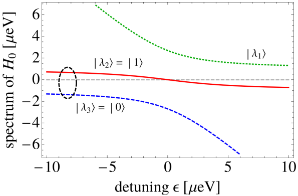
$\Rightarrow$ single spin cooperativity $C = g_{\text{QD}}^2 T_2/\kappa \sim 20 - 100$

Coupling SAWs and Quantum Dots

- $\lambda_{\rm SAW} \gg$ size of DQD: add term $H_{\rm SAW} = \sum V_{\rm SAW}(x_i) n_i$ to $H_{\rm DQD}$
- detuning of $|S_{02}\rangle$ varies periodically with $V_{\rm SAW}$:

$$\begin{aligned} H &= \omega_0(|T_-\rangle\langle T_-| - |T_+\rangle\langle T_+|) - \Delta B(|T_0\rangle\langle S_{11}| + \text{h.c.}) \\ &+ t(|S_{02}\rangle\langle S_{11}| + \text{h.c.}) - (\epsilon - \Delta V_{\rm SAW}(t))|S_{02}\rangle\langle S_{02}| \end{aligned}$$

three eigenstates in $S_z = 0$ subspace:
$|\lambda_l\rangle = \alpha_l |T_0\rangle + \beta_l |S_{11}\rangle + \kappa_l |S_{02}\rangle$
choose $\omega_{\rm SAW}$ resonant with $|\lambda_2\rangle \leftrightarrow |\lambda_3\rangle$



$\Rightarrow$ $H_{\rm eff} = \omega_{\rm eff}(|\lambda_2\rangle\langle\lambda_2| - |\lambda_3\rangle\langle\lambda_3|) + \Omega_{\rm eff}(a|\lambda_2\rangle\langle\lambda_3| + \text{h.c.})$

$\Rightarrow$ single-phonon coupling strength $g_{\rm QD} \sim 10 - 20$MHz possible

$\Rightarrow$ single spin cooperativity $C = g_{\rm QD}^2 T_2/\kappa \sim 20 - 100$

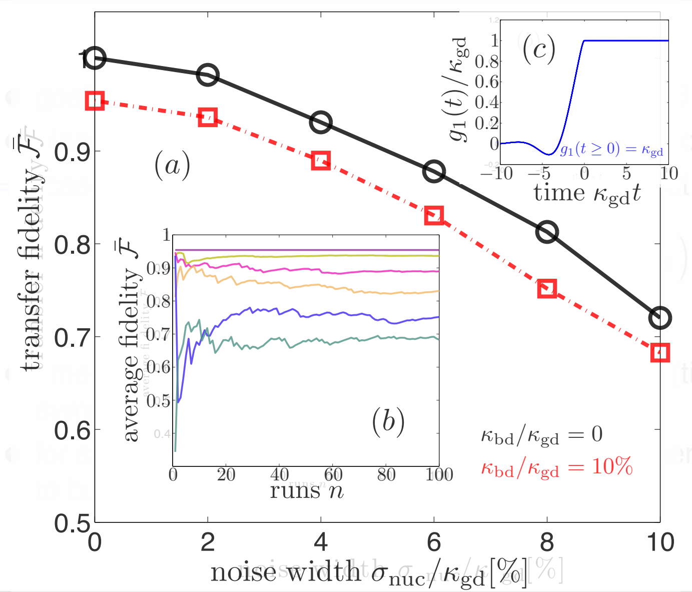
State Transfer Protocol

- goal: realize $(\alpha|0\rangle + \beta|1\rangle) \otimes |0\rangle \to |0\rangle \otimes (\alpha|0\rangle + \beta|1\rangle)$
- place qubits in two cavities connected by wave guide

⇒ "cascaded quantum system": output of first in input of 2nd cavity

$$\begin{aligned}\mathcal{L}\rho &= -i\left[H_S(t) + i\kappa_{\mathrm{gd}}\left(a_1^\dagger a_2 - a_2^\dagger a_1\right), \rho\right] \\ &\quad + 2\kappa_{\mathrm{gd}}\mathcal{D}[a_1 + a_2]\rho + \mathcal{L}_{\mathrm{noise}}\rho\end{aligned}$$

- time dependent control pulses to optimize fidelity (time-reversal symmetric phonon wave packet)
- for small losses: fidelity $F = 1 - \epsilon - C^{-1}$ (C cooperativity, ϵ losses to bulk phonons)



$|1\rangle)$

de

of 2nd cavity

$, \rho]$

time-reversal

rativity, ϵ losses

How cool do we have to be?

- for $\sim$GHz SAWs: 10mK to reach "ground state" (dilution fridge)

? Experimentalist: is that really necessary??? (dilution fridge is $$$)

- complications through thermal occupation: effective coupling strength unknown ($\sim g\sqrt{n_{\rm th}}$), cavity losses enhanced ($\sim \kappa n_{\rm th}$)

★ Nevertheless, Theory says: Not really! *Sørensen-Mølmer*-gate [18], *García-Ripoll-Zoller-Cirac*-gate [4] proposed for trapped ions, that work independent of motional state and make heavy use of well-tuned laser pulses

- we propose another one that does not use lasers, but relies only on integer spectrum of $a^\dagger a$

How cool do we have to be?

- for $\sim$GHz SAWs: 10mK to reach "ground state" (dilution fridge)

? Experimentalist: is that really necessary??? (dilution fridge is $$$)

- complications through thermal occupation: effective coupling strength unknown ($\sim g\sqrt{n_{\mathrm{th}}}$), cavity losses enhanced ($\sim \kappa n_{\mathrm{th}}$)

★ Nevertheless, Theory says: Not really! *Sørensen-Mølmer*-gate [18], *García-Ripoll-Zoller-Cirac*-gate [4] proposed for trapped ions, that work independent of motional state and make heavy use of well-tuned laser pulses

- we propose another one that does not use lasers, but relies only on integer spectrum of $a^\dagger a$

How cool do we have to be?

- for $\sim$GHz SAWs: 10mK to reach "ground state" (dilution fridge)

? Experimentalist: is that really necessary??? (dilution fridge is $$$)

- complications through thermal occupation: effective coupling strength unknown ($\sim g\sqrt{n_{\mathrm{th}}}$), cavity losses enhanced ($\sim \kappa n_{\mathrm{th}}$)

★ Nevertheless, Theory says: Not really! *Sørensen-Mølmer*-gate [18], *García-Ripoll-Zoller-Cirac*-gate [4] proposed for trapped ions, that work independent of motional state and make heavy use of well-tuned laser pulses

- we propose another one that does not use lasers, but relies only on integer spectrum of $a^\dagger a$

How cool do we have to be?

- for $\sim$GHz SAWs: 10mK to reach “ground state” (dilution fridge)

? Experimentalist: is that really necessary??? (dilution fridge is $$$)

- complications through thermal occupation: effective coupling strength unknown ($\sim g\sqrt{n_{\mathrm{th}}}$), cavity losses enhanced ($\sim \kappa n_{\mathrm{th}}$)

★ Nevertheless, Theory says: Not really! *Sørensen-Mølmer*-gate [18], *García-Ripoll-Zoller-Cirac*-gate [4] proposed for trapped ions, that work independent of motional state and make heavy use of well-tuned laser pulses

- we propose another one that does not use lasers, but relies only on integer spectrum of $a^\dagger a$

A "hot" gate for SAW (and other) cavities

- single mode cavity, several qubits

$$H = \omega_c a^\dagger a + \frac{\omega_q}{2} S^z + g\mathcal{S}(a + a^\dagger), \mathcal{S} = \sum \eta_i^r \sigma_i^r$$

- for simplicity: consider limit $\omega_q \to 0$, then

$$H = \omega_c \left(a + \frac{g}{\omega_c}\mathcal{S} \right)^\dagger \left(a + \frac{g}{\omega_c}\mathcal{S} \right) - \frac{g^2}{\omega_c}\mathcal{S}^2$$

★ "displaced a" $\tilde{a} = a + \frac{g}{\omega_c}\mathcal{S}$

⇒ H unitarily equivalent to $H_0 = \omega_c a^\dagger a - \frac{g^2}{\omega_c}\mathcal{S}^2 = U^\dagger H U$ by polaron transformation

$$U = \exp\left[\frac{g}{\omega_c}\mathcal{S}(a - a^\dagger) \right]$$

- since $H = U H_0 U^\dagger$ we have

$$e^{itH} = U e^{itH_0} U^\dagger = U e^{it\omega_c a^\dagger a} e^{-it\frac{g^2}{\omega_c}\mathcal{S}^2} U^\dagger$$

★ at $t_m = \frac{2\pi}{\omega_c} m$ the a-dependent term is $\mathbb{1}$

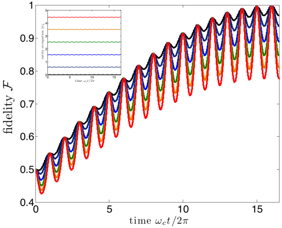
⇒ since U commutes with $\mathcal{S}$ we have *exactly*

$$e^{it_m H} = e^{-i2\pi m (g/\omega_c)^2 \mathcal{S}^2}$$

independent of the motional state

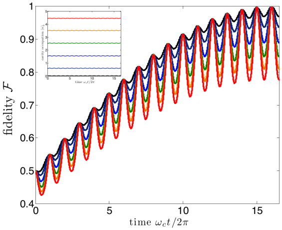
- the $e^{iT\mathcal{S}^2}$ gate can produce Bell states, GHZ states, phase gate...
- see also Royer *et al*, Quantum **1** (2017); arXiv:1603.04424 [16].

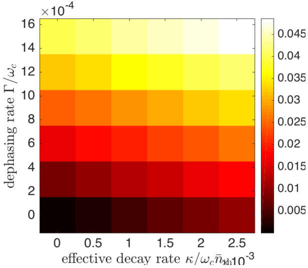
- the scheme works



- small $\omega_q \neq 0$ can be tolerated, too...
- still T-dependent, since rate of losses $\propto \kappa n_{\mathrm{th}}$
- good gate operation at $T = 1K$ possible

- the scheme works even with dephasing and losses



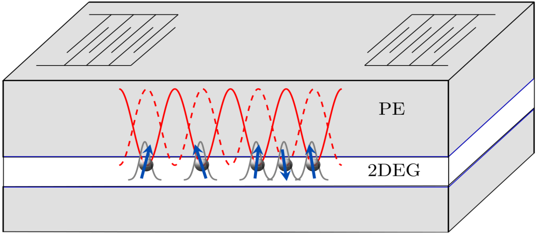


- small $\omega_q \neq 0$ can be tolerated, too...
- still T-dependent, since rate of losses $\propto \kappa n_{\text{th}}$
- good gate operation at $T = 1K$ possible

Acoustic Lattices: Motivation

- trapping electrons in stationary 2d potential
- path to 2D architecture?
- no need for individual fabrication of quantum dots
- quantum simulation Hubbard model and beyond
- related work on *moving* acoustic lattices: Santos group (exp) [11]; Byrnes *et al.*, PRL 2007 [2].

General Idea



- standing SAW imposes potential landscape on electrons in 2DEG
- rapidly oscillating force (GHz)
- slow/inert particle sees an effective time-independent periodic potential (and can become effectively trapped at field nodes)

⇒ stationary, but moveable periodic potential

? do the numbers work out?

Acoustic Lattice I

- single electron interacting with the electric field of a single SAW
- SAW-induced potential (piezoelectric or deformation potential):

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

$\Rightarrow$ classical equation of motion:

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

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

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

$\Rightarrow$ stability regions $0 < q < 0.92$ (cf. trapped ions!)

$\Rightarrow$ slow harmonic secular motion + fast, low-amplitude micro-motion (in stable region...)

Acoustic Lattice I

- single electron interacting with the electric field of a single SAW
- SAW-induced potential (piezoelectric or deformation potential):

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

$\Rightarrow$ classical equation of motion:

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

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

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

$\Rightarrow$ stability regions $0 < q < 0.92$ (cf. trapped ions!)

$\Rightarrow$ slow harmonic secular motion + fast, low-amplitude micro-motion (in stable region...)

Acoustic Lattice I

- single electron interacting with the electric field of a single SAW
- SAW-induced potential (piezoelectric or deformation potential):

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

$\Rightarrow$ classical equation of motion:

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

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

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

$\Rightarrow$ stability regions $0 < q < 0.92$ (cf. trapped ions!)

$\Rightarrow$ slow harmonic secular motion + fast, low-amplitude micro-motion (in stable region...)

Acoustic Lattice I

- single electron interacting with the electric field of a single SAW
- SAW-induced potential (piezoelectric or deformation potential):

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

$\Rightarrow$ classical equation of motion:

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

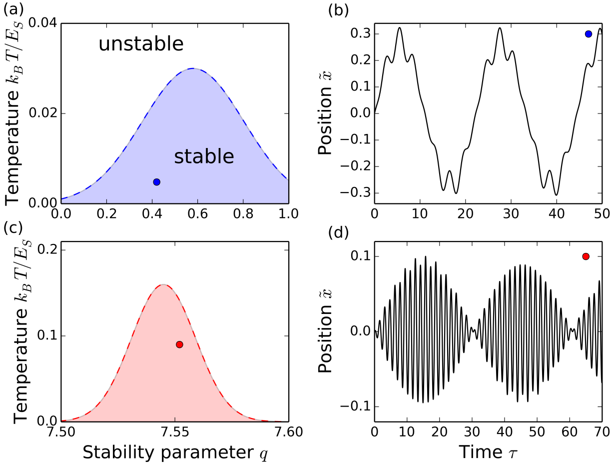
- $E_s \equiv \frac{1}{2} m v_s^2 \equiv \frac{1}{2} m \frac{\omega^2}{k^2}$ and $q \equiv \frac{V_{\mathrm{SAW}}}{E_S}$
- Lamb-Dicke regime $\tilde{x} \ll 1$: Mathieu equation

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

$\Rightarrow$ stability regions $0 < q < 0.92$ (cf. trapped ions!)

$\Rightarrow$ slow harmonic secular motion + fast, low-amplitude micro-motion (in stable region...)

Acoustic Lattice: classical motion



Acoustic Lattice: Quantum Floquet analysis

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

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

$\Rightarrow$ effective time-independent Hamiltonian (for ω large: fast driving)

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

$V_0 = \frac{1}{8} q^2 E_S$: want large E_S! (deep potential, small stab. param. q)

- (1st term of systematic expansion in ω^{-1}, cf Rahav PRA 2003)

★ harmonic approximation (for small kx)

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

$\omega_0 = q\omega/\sqrt{8}$ secular frequency, “trap frequency”

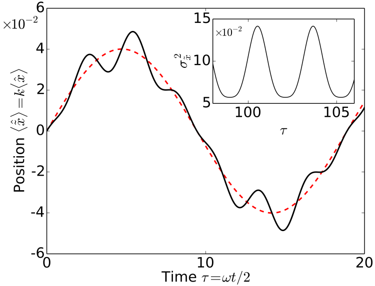
Trajectory of trapped electron

- so far: no losses; now: include dissipation/heating of electron due to other phonon modes

⇒ combine Floquet with Born-Markov approx for bath [cf. Kohler *et al.*, PRE **55** (1997) [10]]

⇒ for $q \ll 1$, obtain time-independent Lindblad master equation for electron motion: damped harmonic oscillator

$$\dot{\rho} \quad = \quad -i\omega_0 \left[a^\dagger a, \rho\right] + \gamma \left(\bar{n}_{\rm th}\left(\omega_0\right) + 1\right) \mathcal{D}\left[a\right] \rho + \gamma \bar{n}_{\rm th}\left(\omega_0\right) \mathcal{D}\left[a^\dagger\right] \rho,$$



Working conditions

- have made a lot of approximations/assumptions

⇒ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

-
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu$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: $\hbar\omega = 100\mu$eV $\implies \hbar\omega_0 \lesssim 20\mu$eV

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

Working conditions

- have made a lot of approximations/assumptions

$\Rightarrow$ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

- Markov approx (short correlation time $\tau_c \sim 1/k_B T$)
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu$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: $\hbar\omega = 100\mu$eV $\implies$ $\hbar\omega_0 \lesssim 20\mu$eV

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

Working conditions

- have made a lot of approximations/assumptions

⇒ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

- thermally stable trap, motional ground state approachable
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu\mathrm{eV}$ (spont emission rate of acoustic phonons); readily compatible with $T = 10 - 100\mathrm{mK}$ ($k_B T = 1 - 10\mu\mathrm{eV}$); SAW frequency $\omega/2\pi = 25\mathrm{GHz}$: $\hbar\omega = 100\mu\mathrm{eV} \implies \hbar\omega_0 \lesssim 20\mu\mathrm{eV}$

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

Working conditions

- have made a lot of approximations/assumptions

$\Rightarrow$ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

- separation of secular and micro-motion time scales ($q \sim \omega_0/\omega \ll 1$)
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu$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: $\hbar\omega = 100\mu\text{eV} \implies \hbar\omega_0 \lesssim 20\mu$eV

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

Working conditions

- have made a lot of approximations/assumptions

$\Rightarrow$ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

- to have at least one bound state per lattice site
  $1 > V_0/\hbar\omega_0 \sim qE_S/\hbar\omega$
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu$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: $\hbar\omega = 100\mu\text{eV} \implies \hbar\omega_0 \lesssim 20\mu$eV

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

Working conditions

- have made a lot of approximations/assumptions

$\Rightarrow$ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

- to have at least one bound state per lattice site
  $1 > V_0/\hbar\omega_0 \sim qE_S/\hbar\omega$
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu$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: $\hbar\omega = 100\mu$eV $\implies$ $\hbar\omega_0 \lesssim 20\mu$eV

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

Working conditions

- have made a lot of approximations/assumptions

$\Rightarrow$ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

- to have at least one bound state per lattice site
  $1 > V_0/\hbar\omega_0 \sim qE_S/\hbar\omega$
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu$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: $\hbar\omega = 100\mu$eV $\implies \hbar\omega_0 \lesssim 20\mu$eV

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

Working conditions

- have made a lot of approximations/assumptions

$\Rightarrow$ chain of (collectively) sufficient conditions for good lattice:

$$\hbar\gamma \ll k_B T \ll \hbar\omega_0 \ll \hbar\omega \ll E_S$$

- to have at least one bound state per lattice site
  $1 > V_0/\hbar\omega_0 \sim qE_S/\hbar\omega$
- note, in particular, that we can't just drive harder, since that moves $q = V_{\mathrm{SAW}}/E_S$ out of stability region; nor just faster (since then we lose the bound states)
- some typical numbers, applicable for GaAs: $\hbar\gamma \sim 0.1\mu$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: $\hbar\omega = 100\mu\text{eV} \implies \hbar\omega_0 \lesssim 20\mu\text{eV}$

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

Can these be realized?

•

⇒

⇒

⇒

Can these be realized?

- electrons in GaAs: $E_S \approx 2\mu\text{eV}$ (for lowest Rayleigh mode)
  $\Longrightarrow \ll 100\mu\text{eV}$: not promising

$\Rightarrow$

$\Rightarrow$

$\Rightarrow$

Can these be realized?

- electrons in GaAs: $E_S \approx 2\mu\text{eV}$ (for lowest Rayleigh mode)
  $\Longrightarrow \ll 100\mu\text{eV}$: not promising

  why? small m_e^*, small speed of sound: E_S too small

$\Rightarrow$

$\Rightarrow$

$\Rightarrow$

Can these be realized?

- electrons in GaAs: $E_S \approx 2\mu\text{eV}$ (for lowest Rayleigh mode)
  $\Longrightarrow \ll 100\mu\text{eV}$: not promising

  why? small m_e^*, small speed of sound: E_S too small

$\Rightarrow$ increase m: holes, use other materials (larger m, larger v_s)

$\Rightarrow$ increase v_s (higher SAW modes; diamond-boosted heterostructures [5, 6])

$\Rightarrow$ other stability regions ($7.5 < q < 7.6$); optimized driving schemes (multi-tone)

Acoustic Lattice: Potential Setups

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. Examples marked with * refer to the lowest SAW mode in GaAs whereas those marked with ** refer to relatively fast (diamond-boosted) values of v_s in diamond-based heterostructures featuring high-frequency SAW and PSAW modes as investigated in Benetti *et al.*, APL (2005) [6], Glushkov *et al.* 2012 [5].

Applications and Issues

★ case study: holes in GaN quantum well on AlN/diamond; use fast SAW mode with $v_s \approx 18$km/s, $m_h = 1.1 m_0$

⇒ RF power $P \approx 0.1$mW (few percent of what “moving QD”-experiments use)

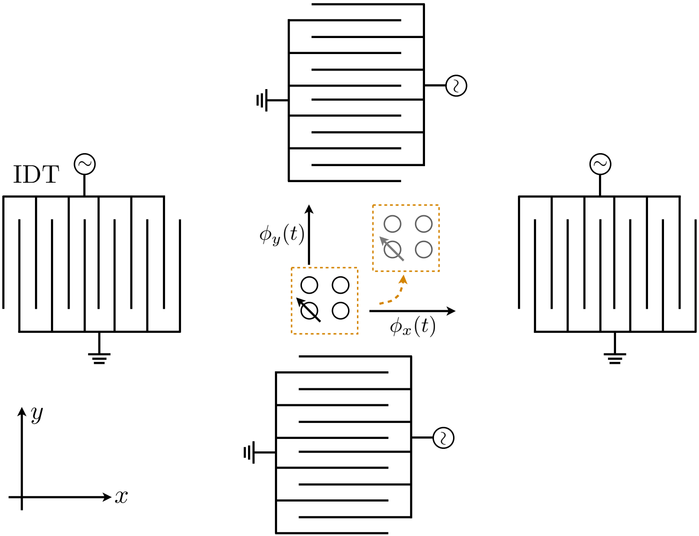
$\hbar\omega$	$q = V_{\mathrm{SAW}}/E_S$	$\hbar\omega_0$	V_0	$n_b = V_0/\omega_0$	$\lambda/2[\mathrm{nm}]$	$d[\mathrm{nm}]$	t	U	$k_B T$
207	0.5 - 0.7	37-51	31-61	0.85-1.2	180	10-100	0.7-1.8	5-270	1-10

Table: Important (energy) scales (in μeV) for an exemplary setup with $E_S = 1\mathrm{meV}$ and $f = 50\mathrm{GHz}$. d denotes the distance between the screening layer and the 2DEG.

- movable quantum dots ($\sim 50\mu$eV deep)
- acoustic lattices for quantum simulations: can realize Fermi Hubbard model

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

Moving QD array



Conclusions

- SAWs provide clean and versatile on-chip method to access different established qubits (QDs, NV, trapped ions, transmons,...)
- can fill similar role as laser field/ cavity-/waveguide modes in cavity-QED and circuit-QED ("QAD")
- SAW modes in quantum regime:
  - qubit in SAW resonator: realization of Jaynes-Cummings system
  - high cooperativities: map spin-qubits to phonons or mediate gates between different qubits
  - temperature-insensitive gates and dynamics
- classical SAW fields to trap, move, couple qubits
  - reliable electron qubit transport over sample-size distances
  - acoustic lattices for electrons or holes in quantum wells
- plenty of promise for quantum technology

Outlook: many open questions

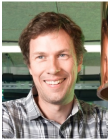
- **quantum acoustics:**
  - more flexible, scalable architectures using SAW flying qubits and SAW resonators?
  - hybrid structures
  - non-classical phons fields for surface physics?
- **acoustic lattices:**
  - heterostructures to engineer/match SAW and quasi-particle properties
  - new parameter regimes for Hubbard model / dipolar lattices?
  - quantum simulation with exotic quasiparticles?

Thanks to my co-workers

MPQ

TUDelft

J Knörzer I Cirac



Harvard U **M Schütz** M Lukin L Vandersypen

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

Schuetz, Knoerzer *et al.*, arXiv:1705.04860

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMIA Y COMPETITIVIDAD

EUSKO JAURLARITZA GOBIERNO VASCO
HEZKUNTZA, HIZKUNTZA POLITIKA ETA KULTURA SAILA
DEPARTAMENTO DE EDUCACIÓN, POLÍTICA LINGÜÍSTICA Y CULTURA

ikerbasque Basque Foundation for Science

Thanks to my co-workers

MPQ

J Knörzer

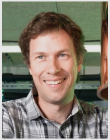
I Cirac

TUDelft

Harvard U

M Schütz

M Lukin



L Vandersypen

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

Schuetz, Knoerzer *et al.*, arXiv:1705.04860

... and thank you for your attention

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
GOBIERNO VASCO
HEZKUNTZA, HIZKUNTZA POLITIKA ETA KULTURA SAILA
DEPARTAMENTO DE EDUCACIÓN, POLÍTICA LINGÜÍSTICA Y CULTURA
ikerbasque
Basque Foundation for Science

Quantum Floquet Analysis

- time-periodic Hamiltonian $H(t+T) = H(t)$

$\Rightarrow$ Floquet theory (cf., e.g., Rahav et al, PRA **68**, 013820 (2003); arXiv:nlin/0301033. Bloch-Floquet theorem: eigenstates of Schrödinger equation

$$i\frac{\partial}{\partial t}|\Psi\rangle = H|\Psi\rangle,$$

have the form

$$|\Psi_\lambda\rangle = e^{-i\lambda t}|u_\lambda(\omega t)\rangle,$$

where u_λ periodic ($u_\lambda(x, \omega(t+T)) = u_\lambda(x, \omega t)$, with $\omega = 2\pi/T$)

- Floquet states: u_λ, "quasi-energy" λ

★ separation of timescales: *slow part* $e^{-i\lambda t}$ ($0 \leq \lambda < \omega$) and a *fast part* $u_\lambda(x, \omega t)$

$\Rightarrow$ find gauge transformation $|\phi\rangle = e^{iF(t)}|\Psi\rangle$ so that effective Hamiltonian for $|\phi\rangle$ is time-independent

$$i\frac{\partial}{\partial t}|\phi\rangle \quad = \quad H_{\mathrm{eff}}|\phi\rangle,$$

References I

- Barnes, C. H. W., J. M. Shilton, and A. M. Robinson (2000), Phys. Rev. B **62**, 8410, cond-mat/0006037.
- Byrnes, T., P. Recher, N. Y. Kim, S. Utsunomiya, and Y. Yamamoto (2007), Phys. Rev. Lett. **99**, 016405, cond-mat/0608142.
- Ford, C. J. B. (2017), physica status solidi (b) **254** (3), 1600658, arXiv:1702.06628.
- García-Ripoll, J. J., P. Zoller, and J. I. Cirac (2003), Phys. Rev. Lett. **91**, 157901, quant-ph/0306006.
- Glushkov, E., N. Glushkova, and C. Zhang (2012), Journal of Applied Physics **112** (6), 064911.
- Benetti, M., D. Cannata, F. D. Pietrantonio, V. I. Fedosov and E. Verona Appl. Phys. Lett. **87**, 033504 (2005).
- Gustafsson, M. V., T. Aref, A. F. Kockum, M. K. Ekström, G. Johansson, and P. Delsing (2014), Science **346**, 207, arxiv:1404.0401.

References II

Hermelin, S., B. Bertrand, S. Takada, M. Yamamoto, S. Tarucha, A. Ludwig, A. D. Wieck, C. Bäuerle, and T. Meunier (2017), physica status solidi (b) **254** (3), 1600673.

Hermelin, S., S. Takada, M. Yamamoto, S. Tarucha, A. D. Wieck, L. Saminadayar, C. Bäuerle, and T. Meunier (2011), Nature **477**, 435, arXiv:1107.4759.

Kohler, S., T. Dittrich, and P. Hänggi (1997), Phys. Rev. E **55**, 300, quant-ph/9809088.

de Lima Jr, M. M., and P. V. Santos (2005), Rep. Prog. Phys. **68** (7), 1639.

Loss, D., and D. P. DiVincenzo (1998), Phys. Rev. A **57**, 120, cond-mat/9701055.

Manenti, R., M. J. Peterer, A. Nersisyan, E. B. Magnusson, A. Patterson, and P. J. Leek (2016), Phys. Rev. B **93**, 041411, arXiv:1510.04965.

McNeil, R. P. G., M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer and D. A. Ritchie Nature **477**, 439 (2011).

References III

- Rahav, S., I. Gilary, and S. Fishman (2003), Phys. Rev. A **68**, 013820, nlin/0301033.
- Royer, B., A. L. Grimsmo, N. Didier, and A. Blais (2017), Quantum **1**, 11, arXiv:1603.04424.
- Shulman, M. D., O. E. Dial, S. P. Harvey, H. Bluhm, V. Umansky, and A. Yacoby (2012), Science **336** (6078), 202.
- Sørensen, A. S., and K. Mølmer (2000), Phys. Rev. A **62**, 022311, quant-ph/0202073.