Quantum Acoustics:

Surface acoustic waves (SAWs) come across qubits

Single-electron quantum dots moving in SAWs minima: conversion to photons

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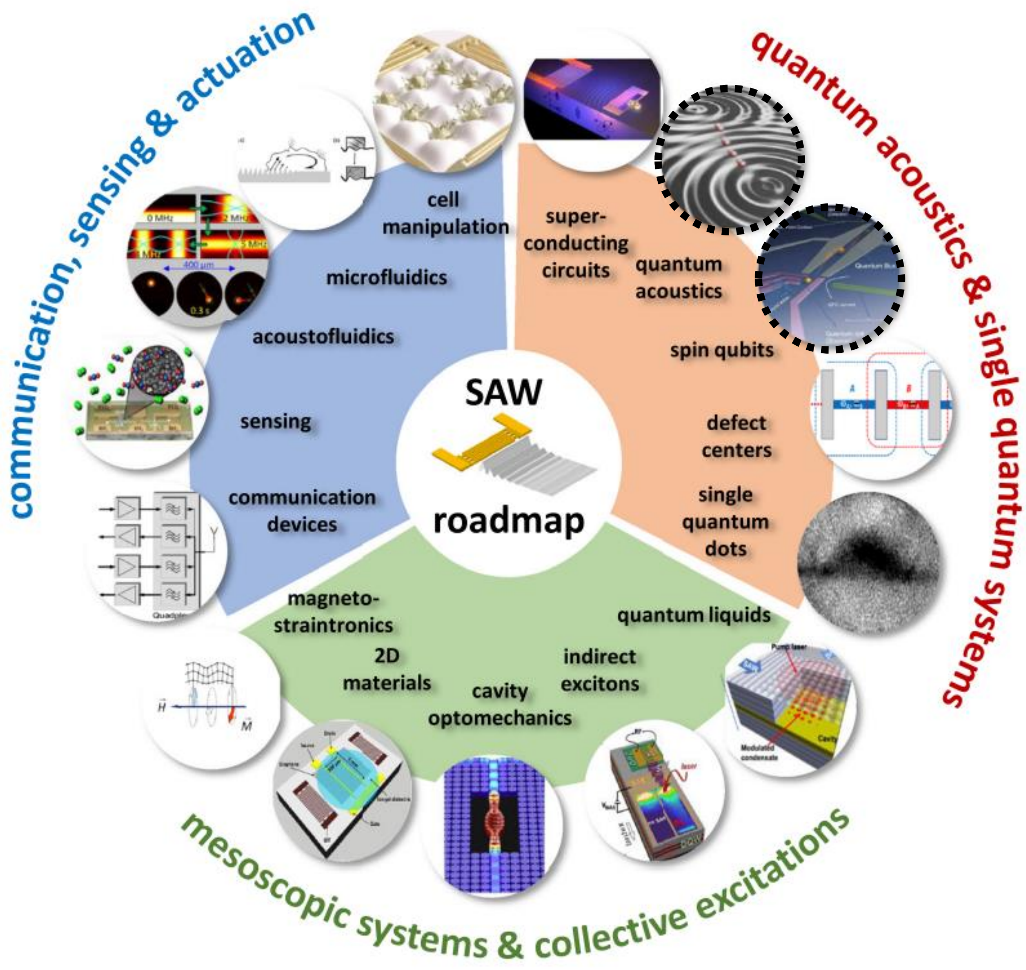
Introductions



P. Delsing *et al*., Journal of Physics D: Applied Physics (2019)

Research on electronics and sensors

- Confined close to the surface
- Coherently excited & detected with microwave electronics
- Stored in compact high-quality resonators over millimeter distances
- Properties can be engineered by choice of material and heterostructures

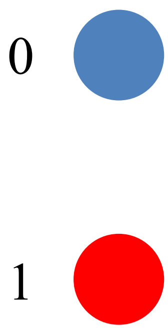
Research on quantum devices

- Sound (phonons) replacing light (photons) and artificial atoms and quasiparticles taking over the role of natural atoms
- Provide moving potential wells towards quantum channels for single electrons

Quantum computing

Bit

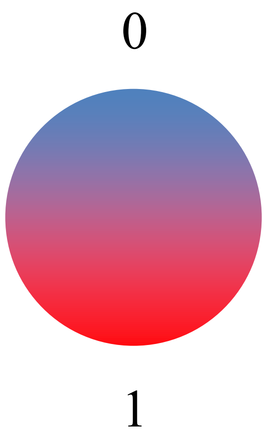
- Classical computing



- Binary system
- 0 or 1
- N (ex. N=20)

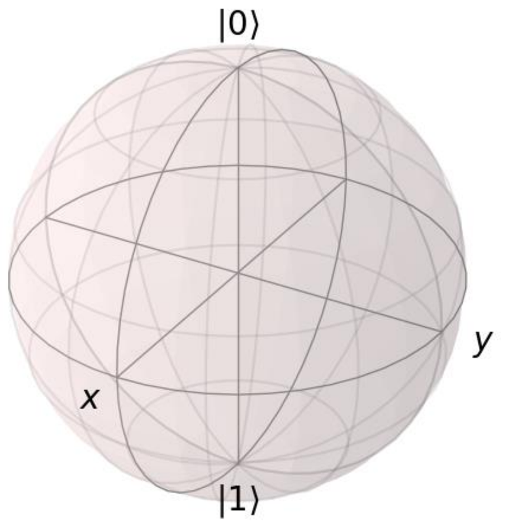
Qubit

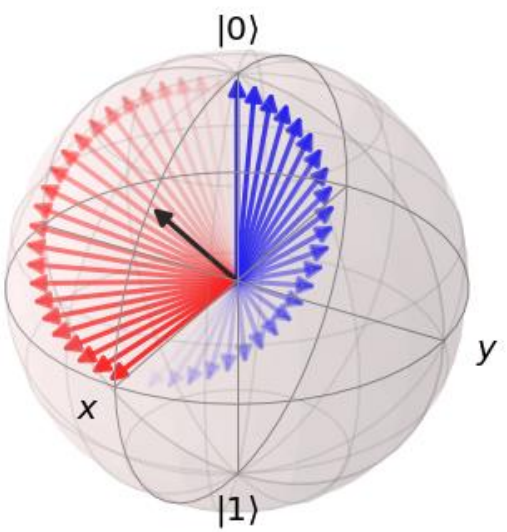
- Quantum computing



- Arbitrarily two-state quantum system
- Superposed states of 0 and 1
- 2^N (ex. N=20, 2^{20}=1,048,576)

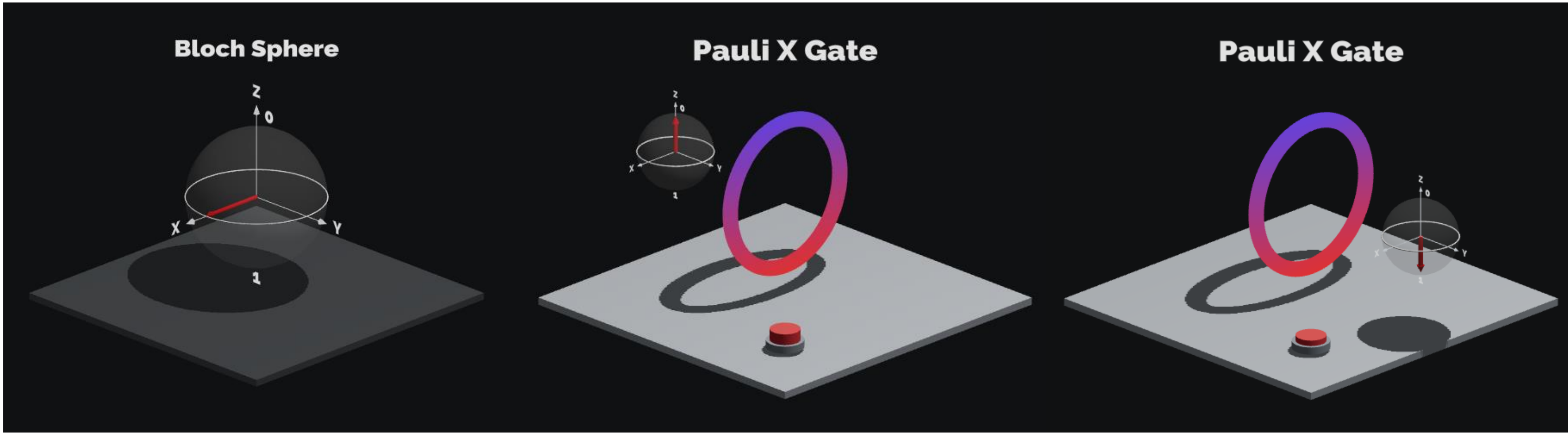
Bloch sphere: superposition





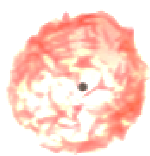
- Electron have a property called spin, whose states are either "up" or "down" (along some axis)
  - origin of permanent magnets
- Think of the two spin states as "north" and "south" poles (written $|0\rangle$ and $|1\rangle$)
- A particle can be in mixture ("superposition") of these two states
- This corresponds to a position somewhere on a "Bloch" sphere: $|Q\rangle = \alpha|0\rangle + \beta|1\rangle$, where α^2 is P_0 and β^2 is P_1
- Control of α and β is related to "quantum logic gate"
- Can position the spin on the equator, and rotate it to any other point on the sphere
- This is called a quantum bit, or "qubit"

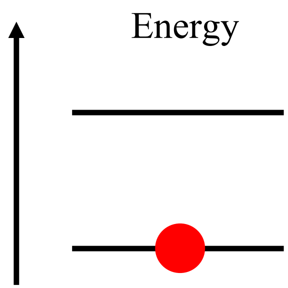
Quantum logic gate



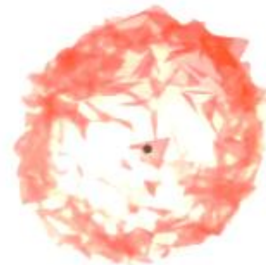
$$X|0\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle \qquad X|1\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle$$

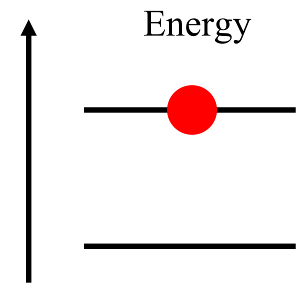
Electron spin resonance



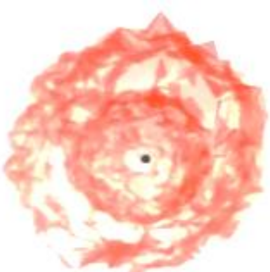


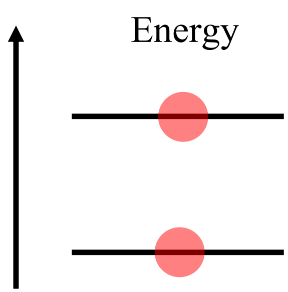
- Not excited state





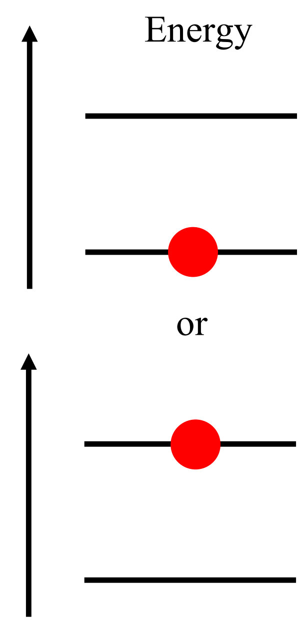
- Excited state



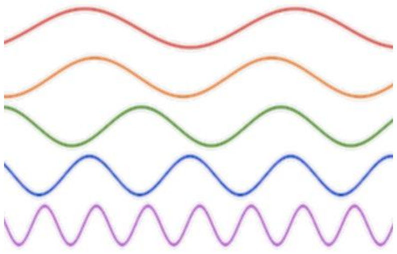


- Superposition of state

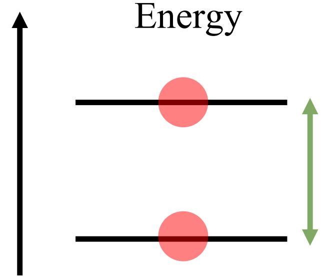
or



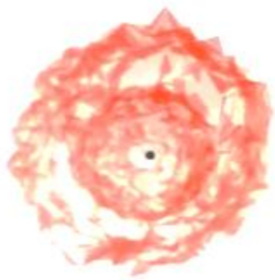
Electron spin resonance



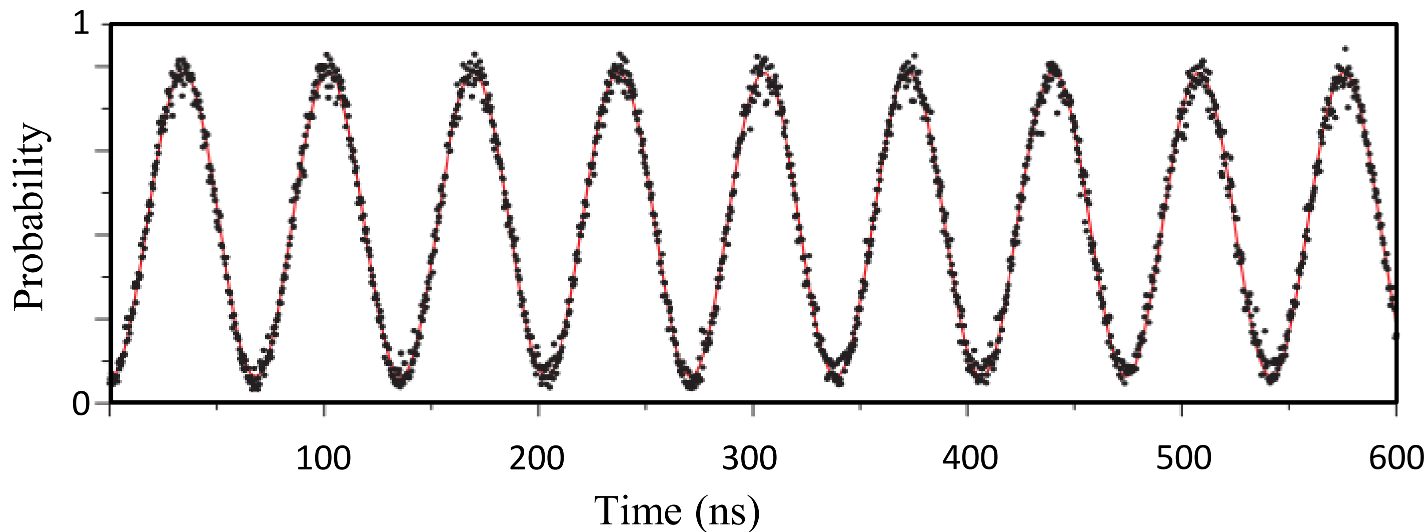
- Electromagnetic wave



- When EM wave is set with proper frequency

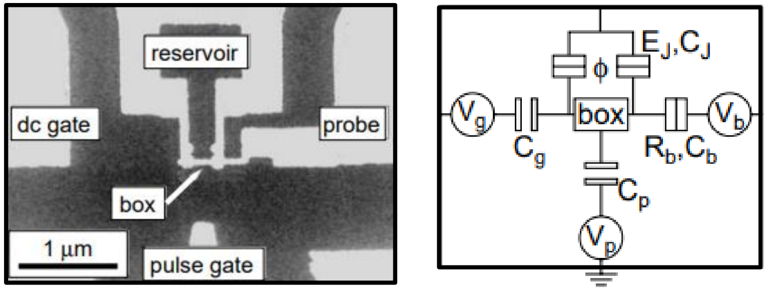


- Alternate progressively between a non-excited & excited state



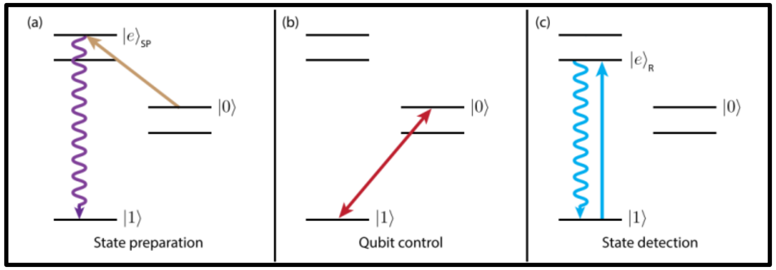
Type of qubit

Superconducting qubit



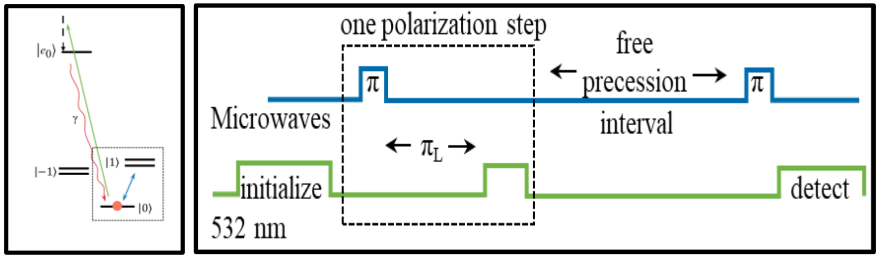
Y. Nakamura *et al*., Nature (1999)

Ion-trap qubit



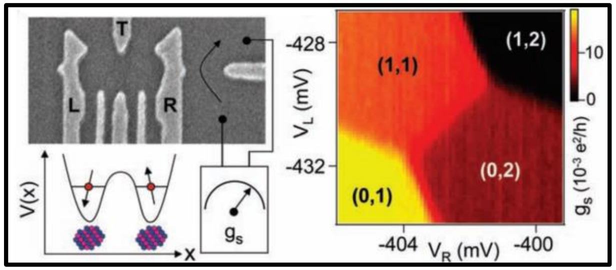
D. Kielpinski *et al*., Nature (1992)

Diamond-NV centre based qubit



M.V. Gurudev Dutt *et al*., Science (2007)

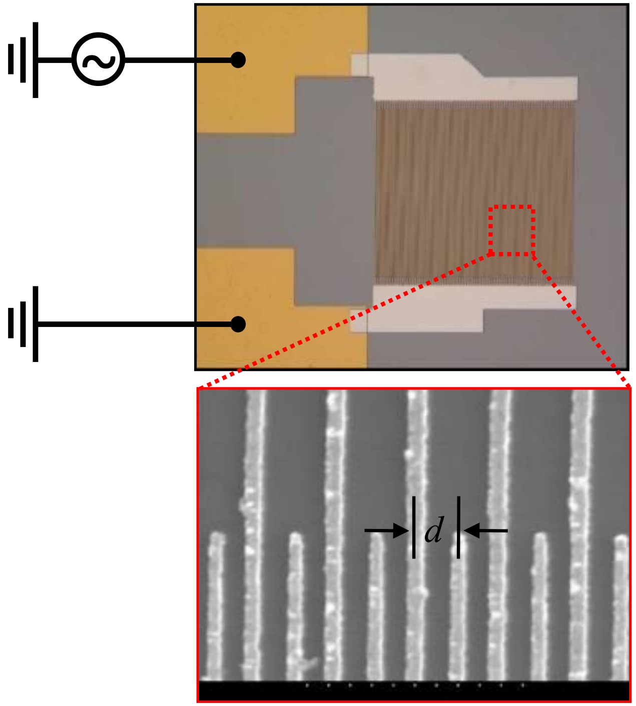
Quantum dot based qubit (spin qubit)



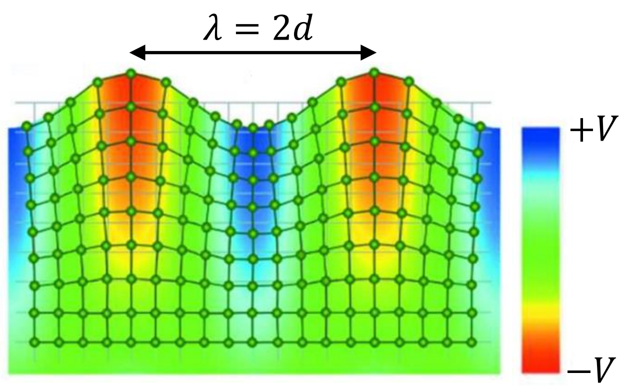
J. R. Petta *et al*., Science (2004)

Surface acoustic waves (SAWs)

Interdigitated transducer for the creation of SAWs



Interdigitated transducers



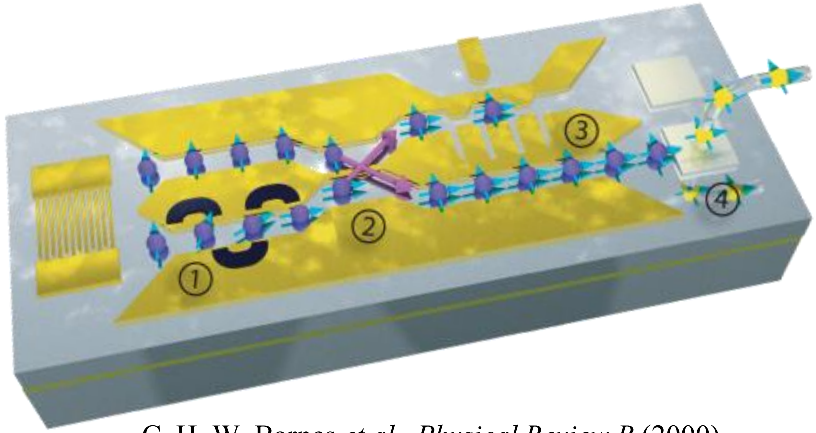
Piezoelectrical material (GaAs)

- Resonant frequency, $f = \frac{v}{\lambda}$
- v : SAW velocity
- λ : SAW wave length
- 1 μm SAW ~ 2.8 GHz on GaAs

- at 2.8 GHz the wave length is 1 μm
- in practice, $f = \sim 2.7$ GHz because of thermal contraction. & mass-loading of the surface caused by the IDT.
- in a piezoelectric material the strain wave is accompanied by a potential wave
- this potential wave can drag electrons along in the 2DEG

SAW-driven quantum processor

The idea is to use the spin of the single electrons trapped in SAW potential minima as qubits:



C. H. W. Barnes *et al.*, *Physical Review B* (2000)

① Magnetic split gates: spin manipulation

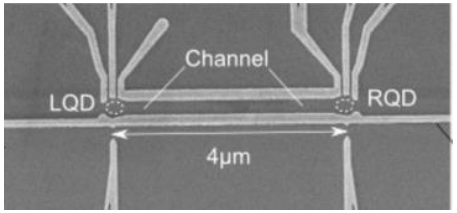
② Tunneling barrier

③ Coherent quantum state

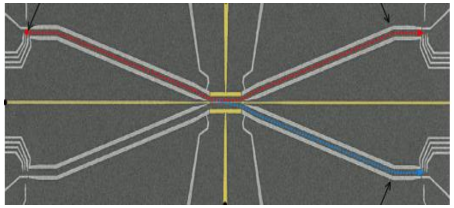
④ Spin readout gates

- A single electron is trapped in each SAW potential minimum and is transported through a depleted 1D channel.
- High-frequency qubit operations can be made by patterned surface gates/nanomagnets laid out on the chip.
- A number of identical operations are repeated at the SAW frequency.
- A scope for quantum information transfer to different qubit schemes (photon/static quantum dots).

SAW quantum dot to static quantum dot

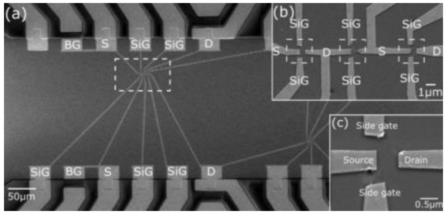


R. P. G. McNeil *et al.*, *Nature* (2011)



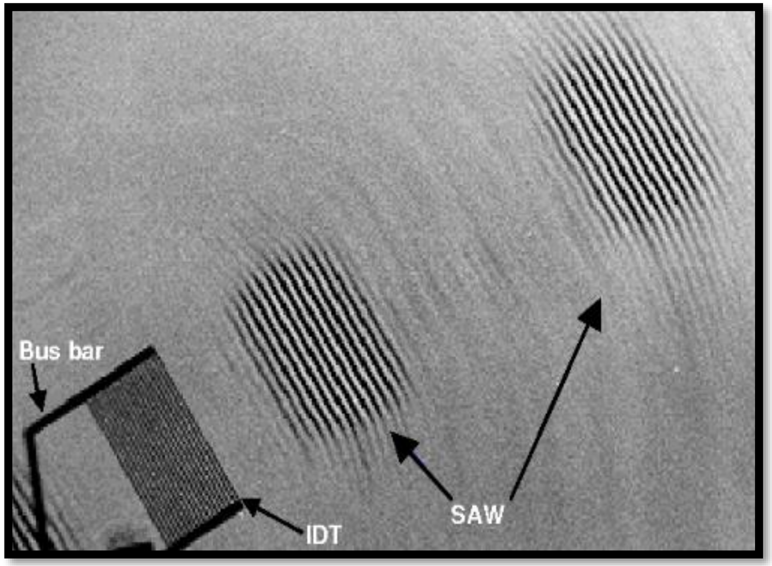
S. Takada *et al.*, *Physical Review B* (2019)

SAW quantum dot to photon

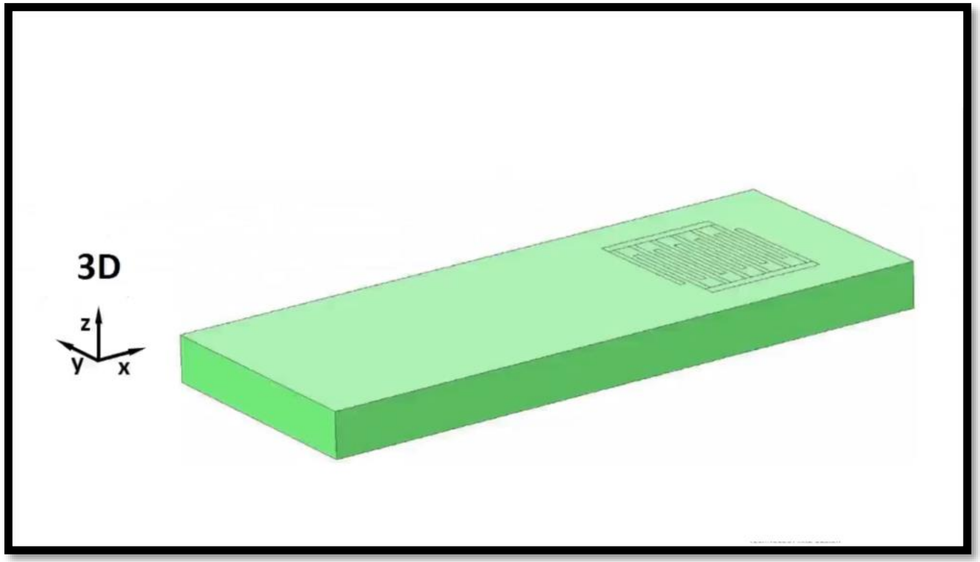


Y. Chung *et al.*, *Physical Review B (2019)*

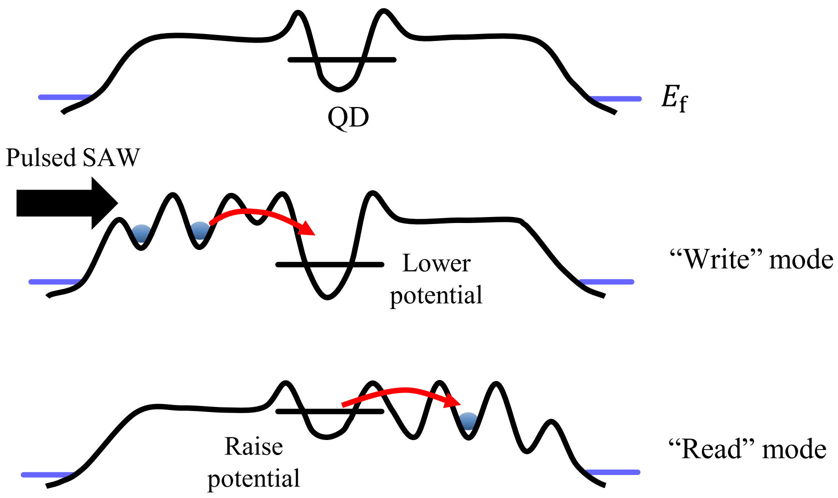
SAWs on the piezoelectric material surface



L. M. Reindl *et al.*, *IEEE* **51**, 11 (2004)

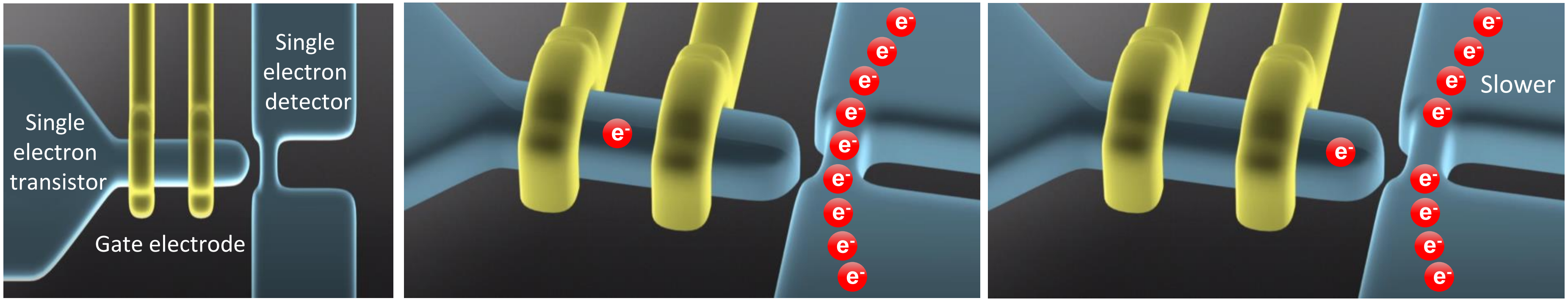


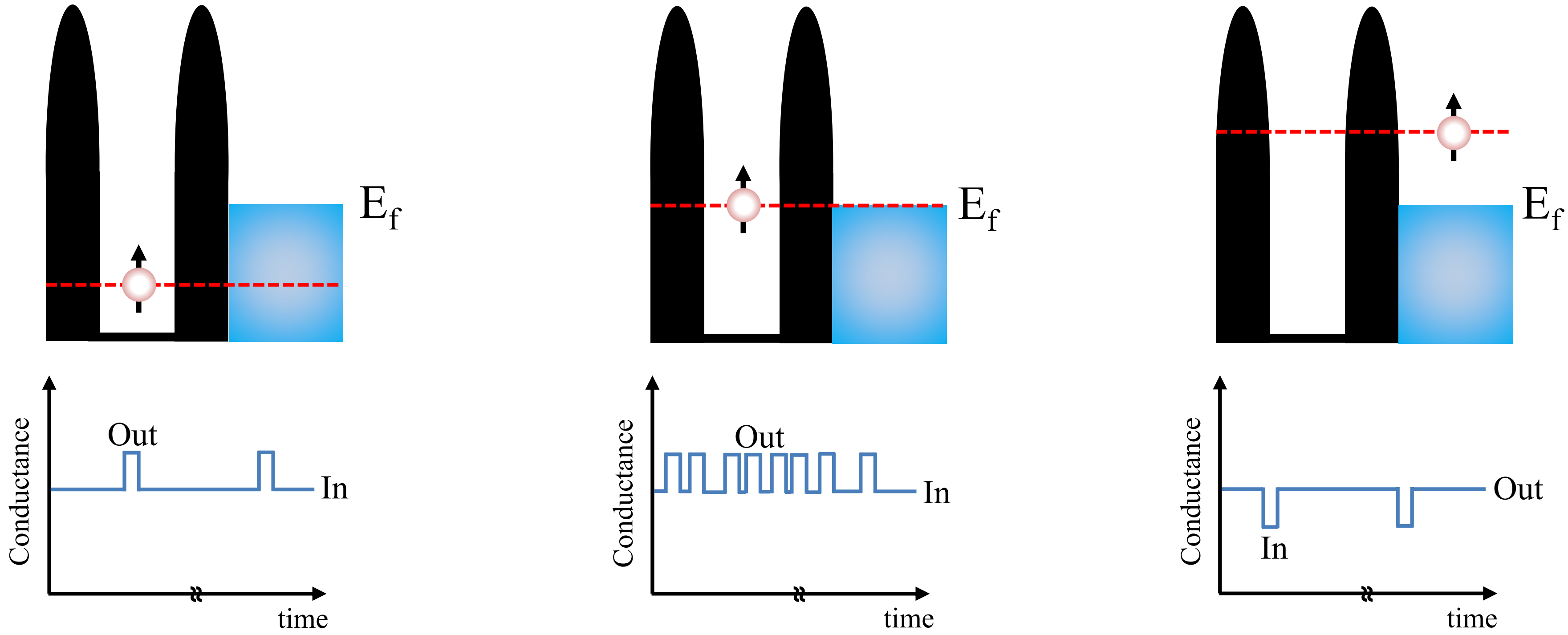
SUTD YouTube D. J. Collins channel (2018)



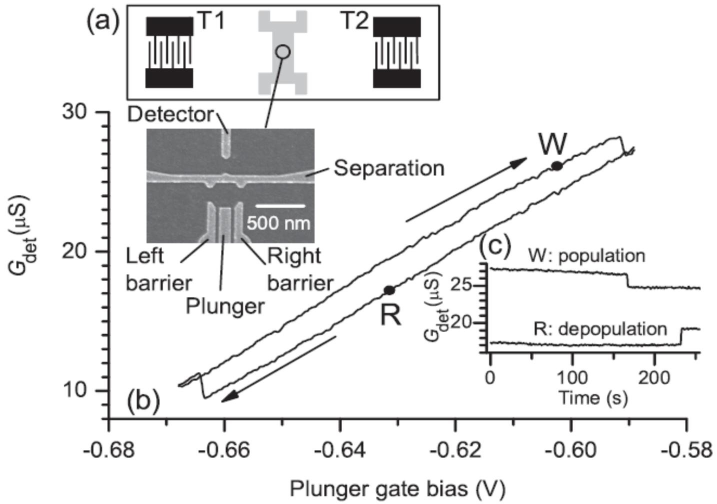
- Single-electron population & depopulation of an isolated quantum dot by a SAW has been demonstrated.
- This mechanisms may form the basis of write & read processes using the electron's spin or charge as a qubit.
- SAW-driven quantized charge pumping can be controllable using a QD.

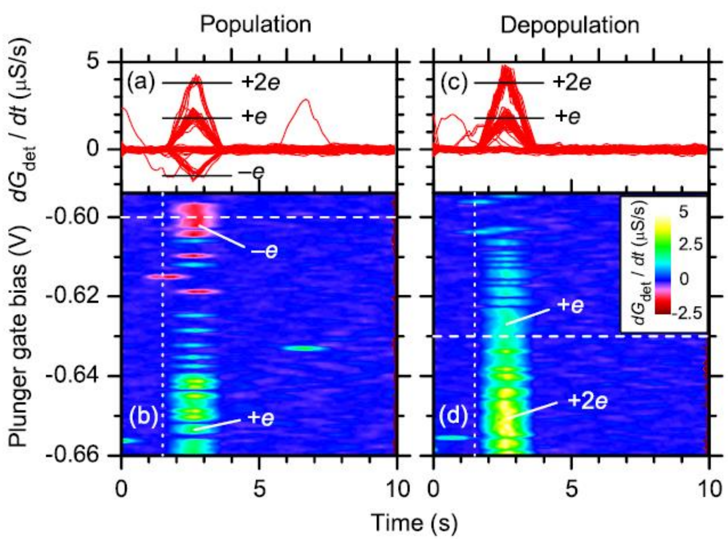
Detection of single-electron transport



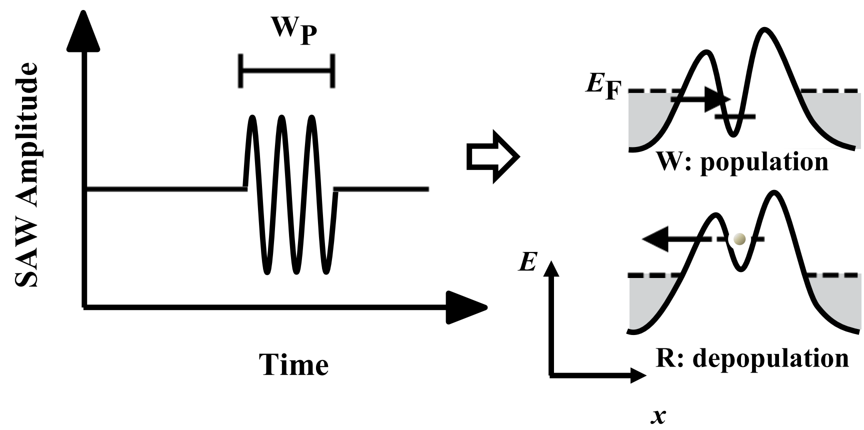


Interaction of SAWs with a static quantum dot



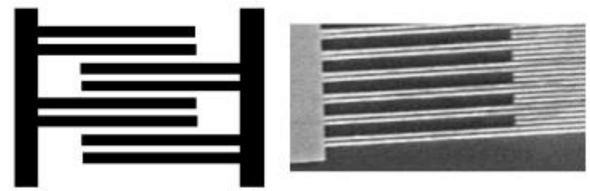
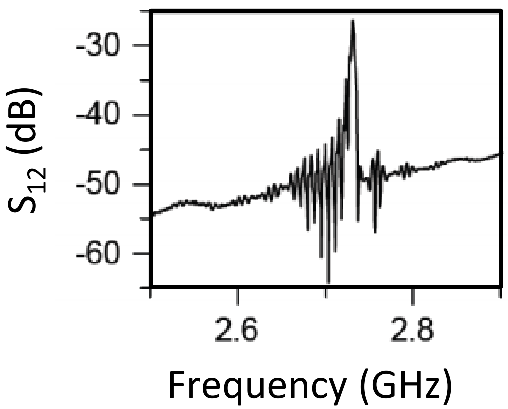
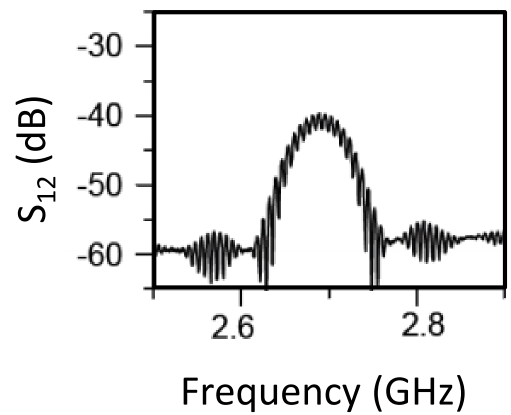


a SAW pulse

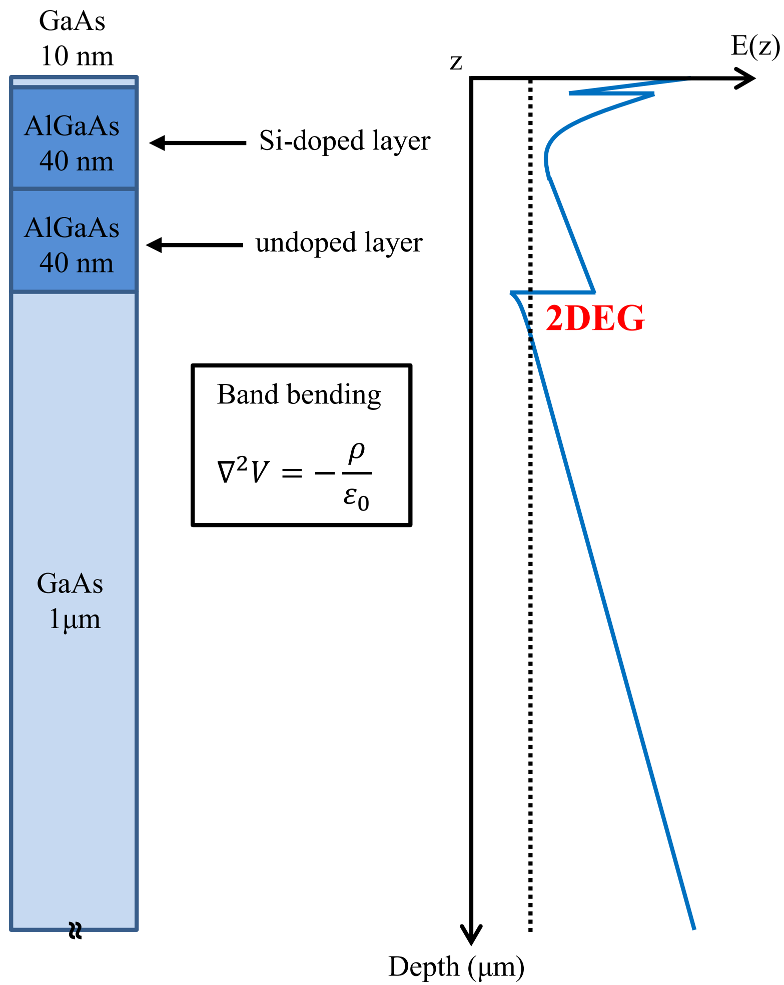


- A SAW pulse can be used to populate/depopulate an isolated quantum dot
- A quantum dot is isolated for reservoirs by large barrier potentials.
- An empty (or occupied) state is set below (or above) the Fermi energy.
- Due to large barrier potentials, the dot stays in this non-equilibrium charge state for ~ 100 s
- When a SAW pulse is sent through the dot, the potential modulation of the barrier of the barrier forces the dot into charge equilibrium, populating (or depopulating) the dot by one electron.
- This method can be used to transfer an electron between a SAW dynamic dot and a gate-defined static dot.

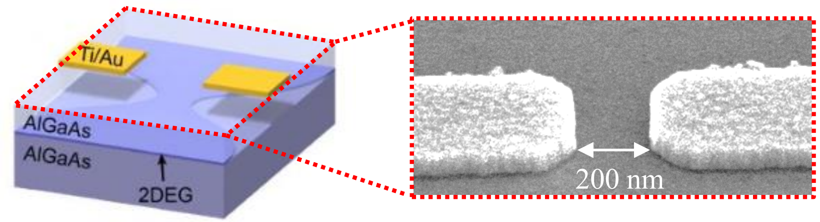
Interdigitated transducer (IDT)

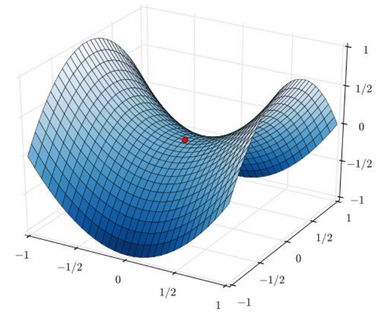
	Uniform single fingers	Split (double) fingers
Finger design		
SAW signal	 • Band width is ~ 3 MHz (with 80 pairs of fingers)	 • Band width is ~ 80 MHz (with 80 pairs of fingers)
Q-factor	• Useful for continuous-wave operation • Useful for long pulses (larger than 1 μs) • Provide a good SAW-current quantisation • Serious thermal heating issue	• Useful for pulsed-wave operation • Useful for short pulses (less than 500 ns) • Fair SAW-current quantisation • Less thermal heating issue

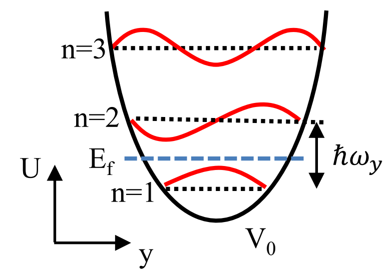
GaAs/AlGaAs heterostructure and gates

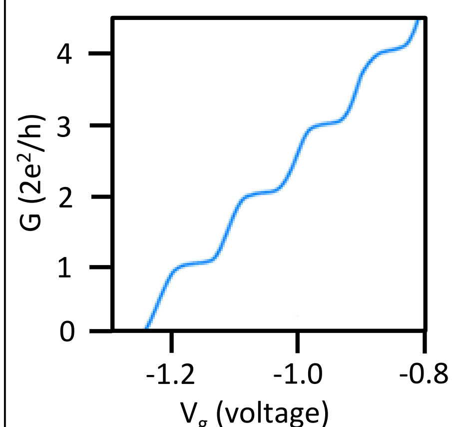


- We need to confine electrons to make an artificial atom
- Starting material is a 2D layer of electrons just below the surface of a GaAs wafer
- Put doping (impurities) in a layer away from the 2DEG





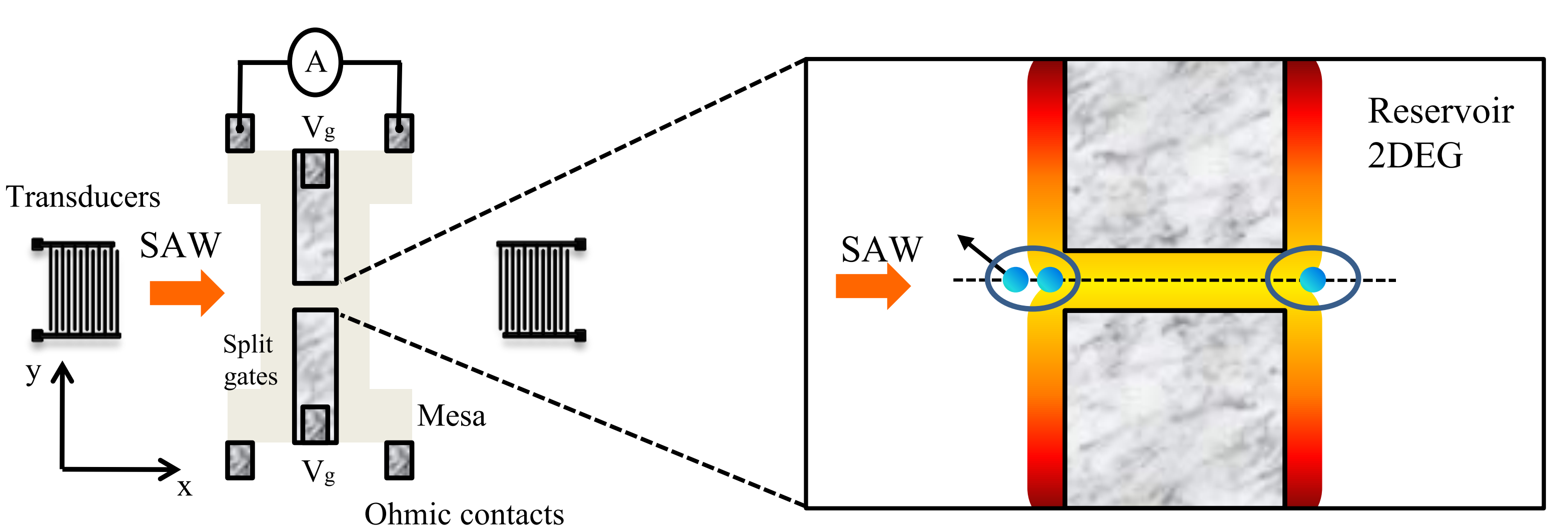




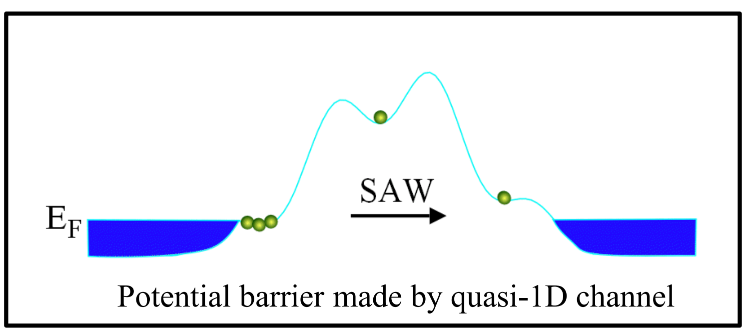
$$G = \frac{2e^2}{h} N$$

- Band offset: 2D potential well
- Doping offset from well
  - very little scattering
  - 2D electron gas (2DEG)
- Gates on surface deplete 2DEG
  - narrow channel between split gates
  - very flexible technique

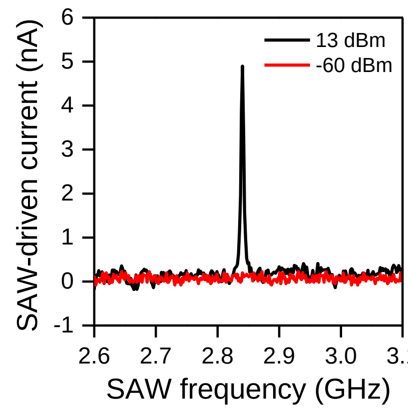
Quantized SAWs-driven electron transport

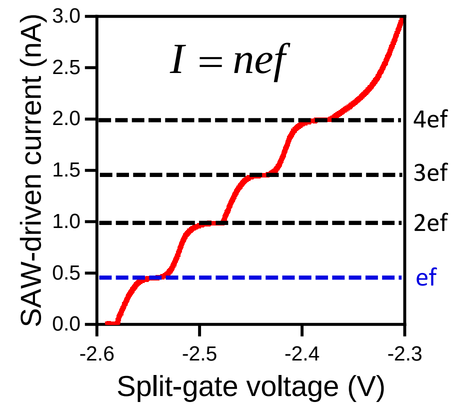


Schematic diagram of a SAW device consisting of interdigitated electrodes



SAW-driven electron pumping process



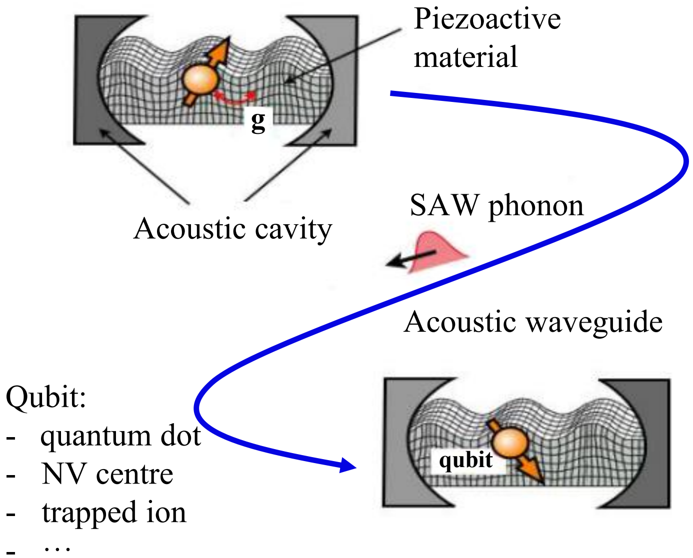


SAWs-driven single electron transport (dynamic quantum dots)

Gating- vs SAW-dependent electron transport

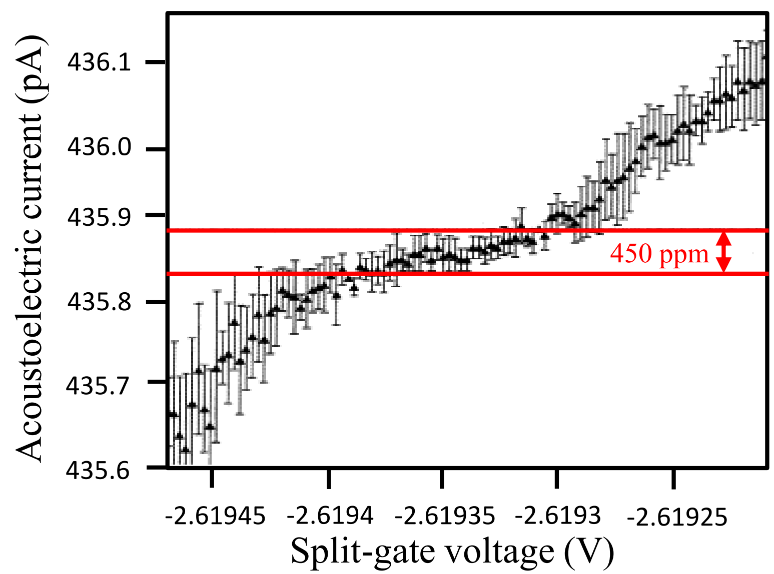
Gating	SAW
	
• Loading – Capturing – Unloading process is dependent on the gating (10 ~ 500 MHz range)	• Loading – Capturing – Unloading process is dependent on SAW propagation (~ GHz range)

Why dynamic quantum dots? Pros & Cons

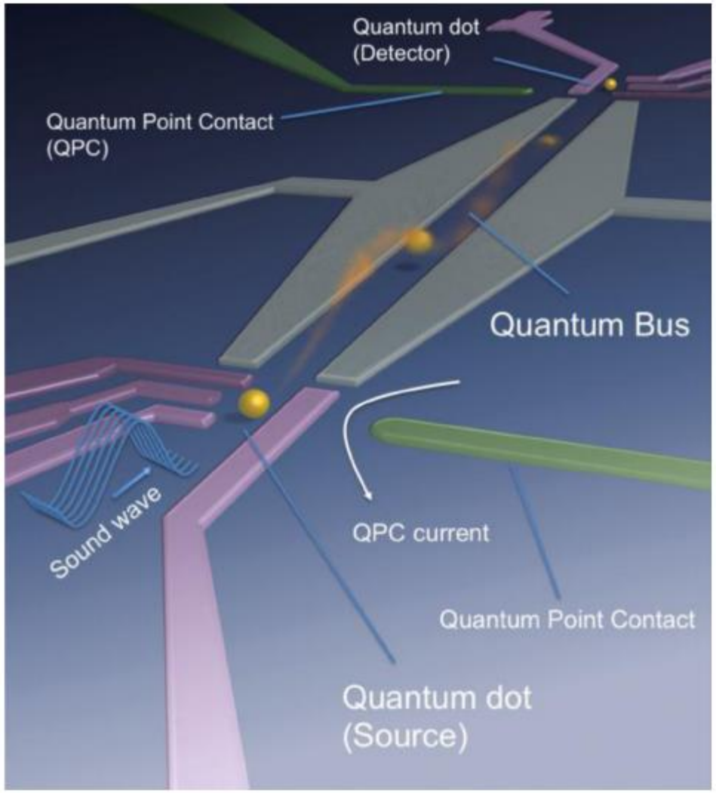


- Can see DC current with no applied bias
- The steps of quantized current are at multiples of *e·f*: metrology of current standard
- Powerful framework to connect other qubit regimes
- In-flight manipulation (compared to photons)
  - enough time manipulate a SAW
- Coupling to optical photons
  - can send quantum information over large distance
- Ultrastrong coupling between SAWs & electrons

- Applying an oscillating voltage to the IDTs causes a free-space electromagnetic (EM) wave to propagate
- Vey sensitive to the surface condition
- If the efficiency of piezoelectric material is not good, thermal heating issue cannot be avoided.
- Not good enough accuracy (~450 ppm) for requirements of quantum computing

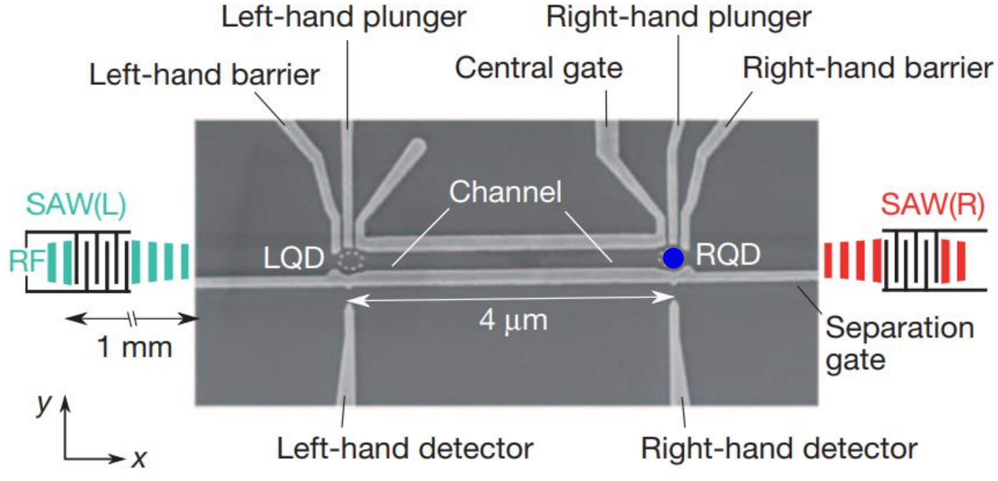


Transfer of quantum information



P. Delsing et al., J. Phys. D. Phys (2019)

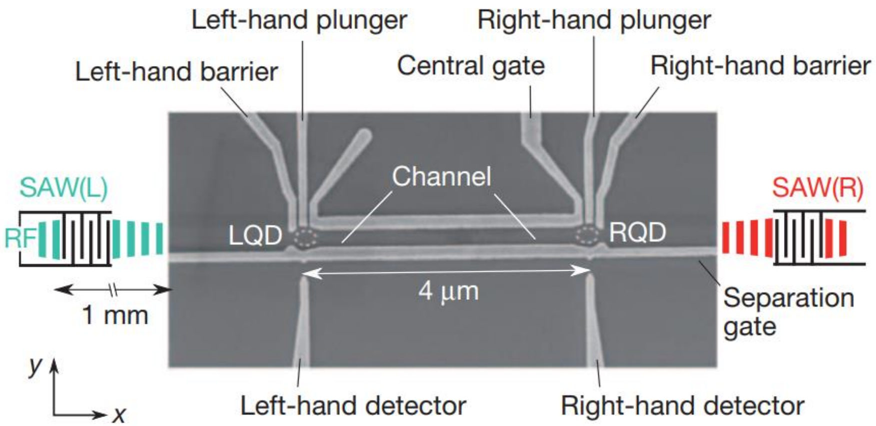
Single electron control by SAWs



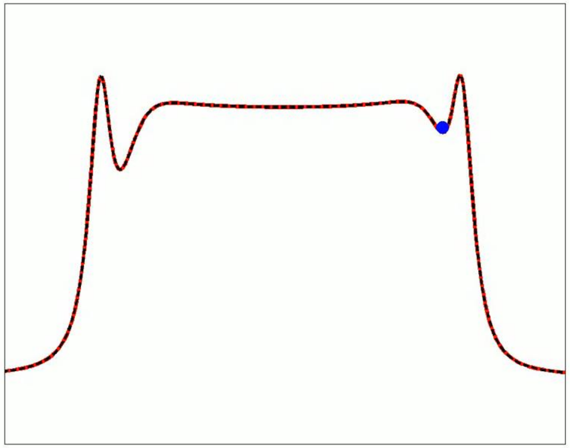
R. P. G. McNeil *et al.* Nature (2011)

- A quantum computer will need to be able to move qubits to entangle adjacent ones or to store and retrieve qubits: quantum repeater
- Transfer spin qubits from static dots to "flying" qubits: SAW-driven qubits, photon qubits
- The devices designed to transfer single electrons over long distances (4 μm) back and forth between static dots:
  - can play with a given electron for e.g. 10 minutes
  - spin transport and coherence still remain to be demonstrated….

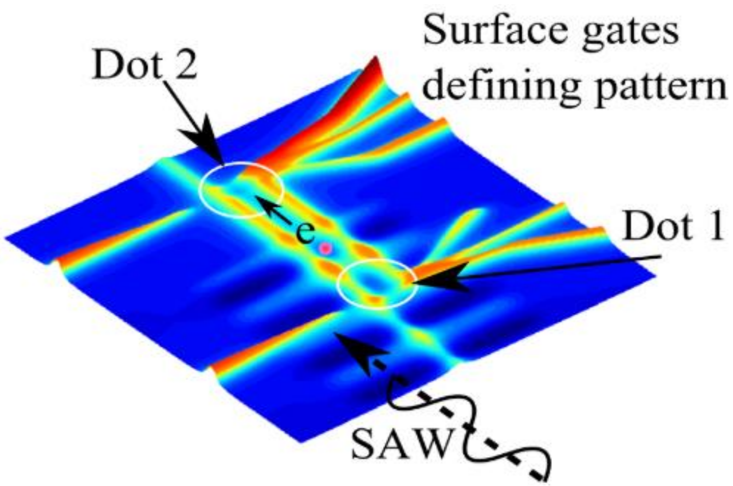
Single-electron ping pong

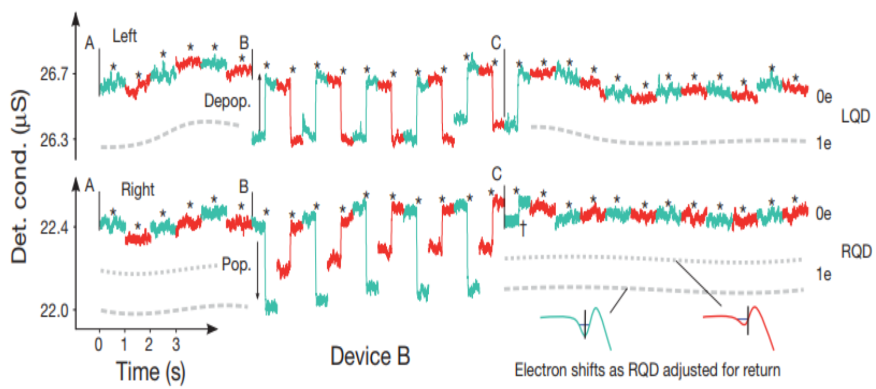


R. P. G. McNeil *et al. Nature* (2011)



Fire a SAW pule (100 ns)

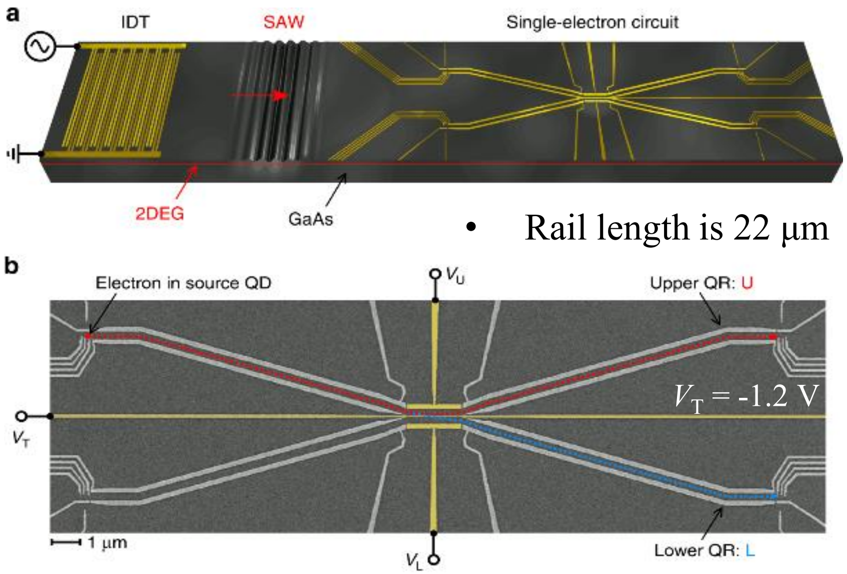




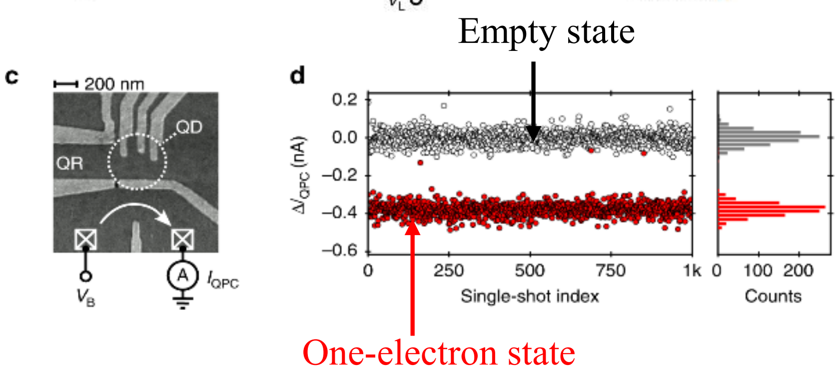
Detect electron population and depopulation:
can transfer 60 times (0.25 mm!)

SAW-driven single-electron transfer

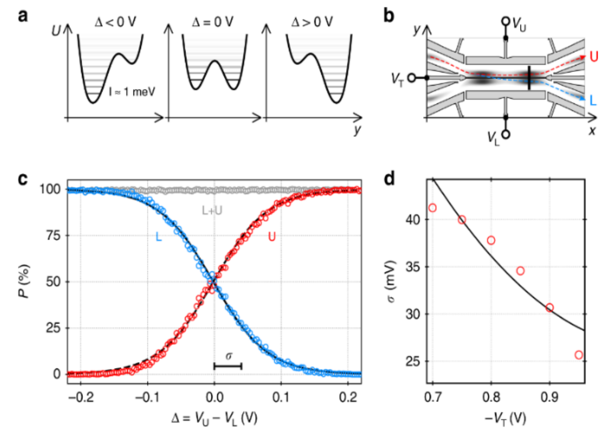
SAW quantum computation



- Rail length is 22 µm



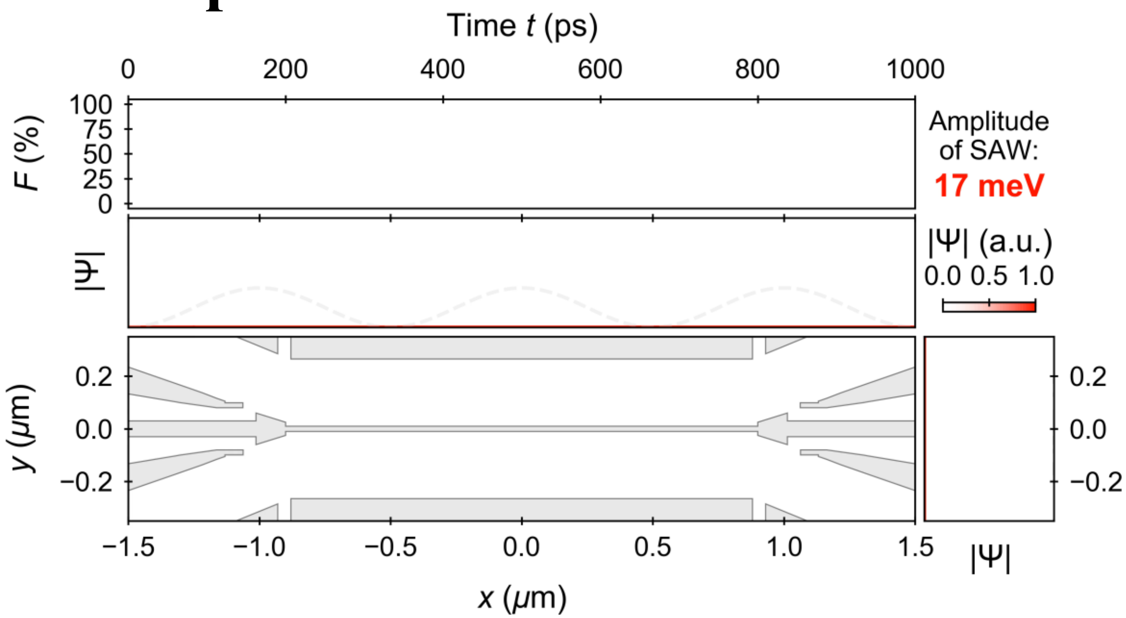
- Error rate of loading is ~ 0.07 %
- Error rate of catching is ~ 0.18 %
- Transfer efficiency along 20 µm is ~ 99.75 %

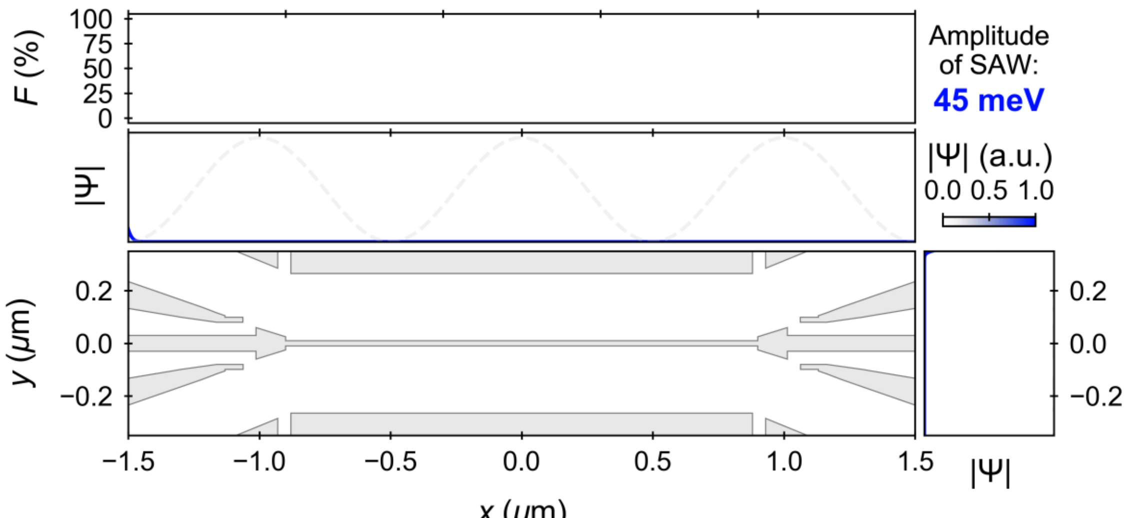


- Couple the two channels to partition an electron
- Coupling is to prepare a superposition state of electron qubit
- The total efficiency is ~ 99.5 %
- The observed probability transition follows Fermi-Dirac distribution, $P_U(\Delta) \approx 1/(\exp(-\Delta/\sigma)+1)$: can be described in terms of single-particle energy state.

S. Takada *et al.*, *Nature Communications* (2019)

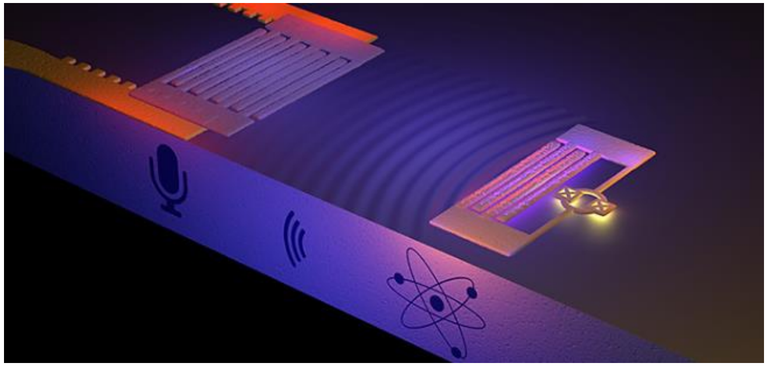
SAW quantum computation





S. Takada *et al.*, *Nature Communications* (2019)

Conclusions: SAW part



- Dynamic dots are interesting objects with applications in quantum computing
  - generate with a SAW in a long channel

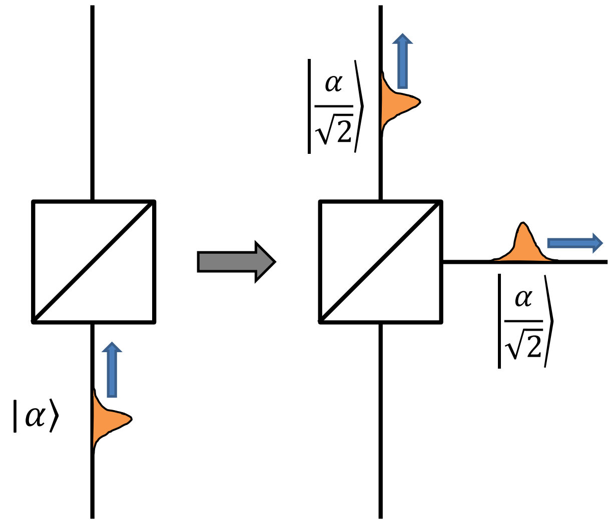
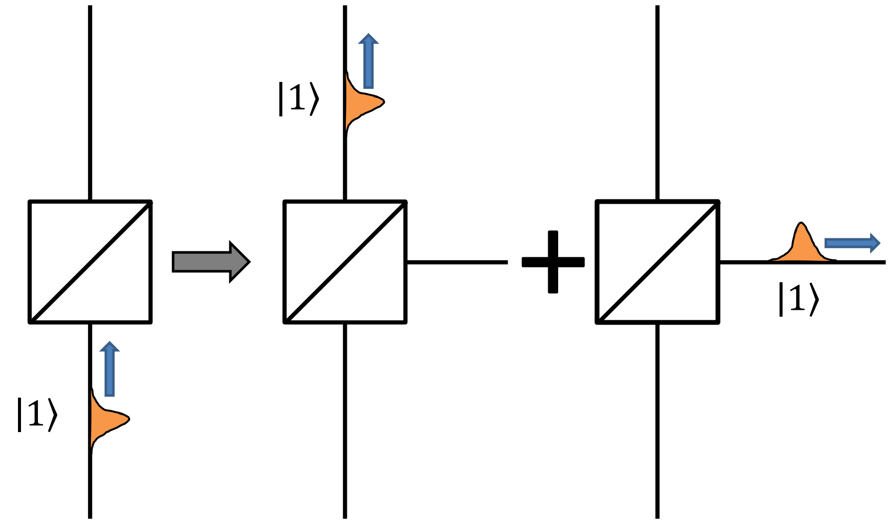
- SAWs can transfer an electron back and forth between two quantum dots
  - couple qubits, transfer to/from quantum memory?
  - electron "ping pong"
  - next step: polarize spin and read it optically

- Single electron in a moving quantum dot can oscillate coherently
  - non-adiabatic transition in channel excites electron into combination of ground and first excited states, producing coherent oscillations t persist for more than 500 ps

- SAWs can transfer an electron back and forth between two quantum dots
  - couple qubits, transfer to/from quantum memory?
  - electron "ping pong"
  - next step: polarize spin and read it optically

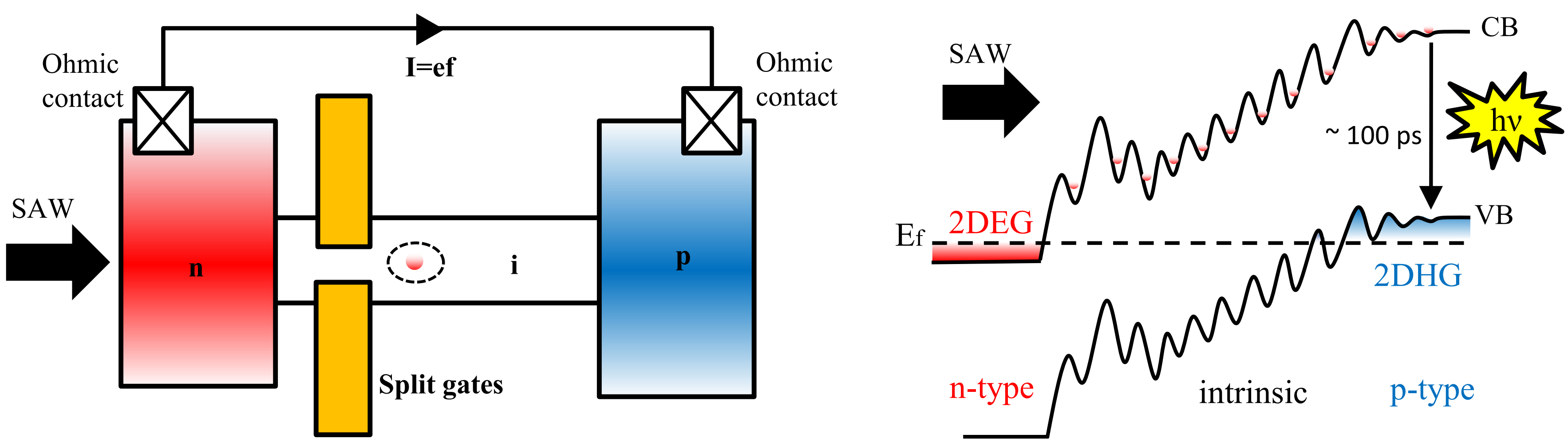
Contents

Why single photon?

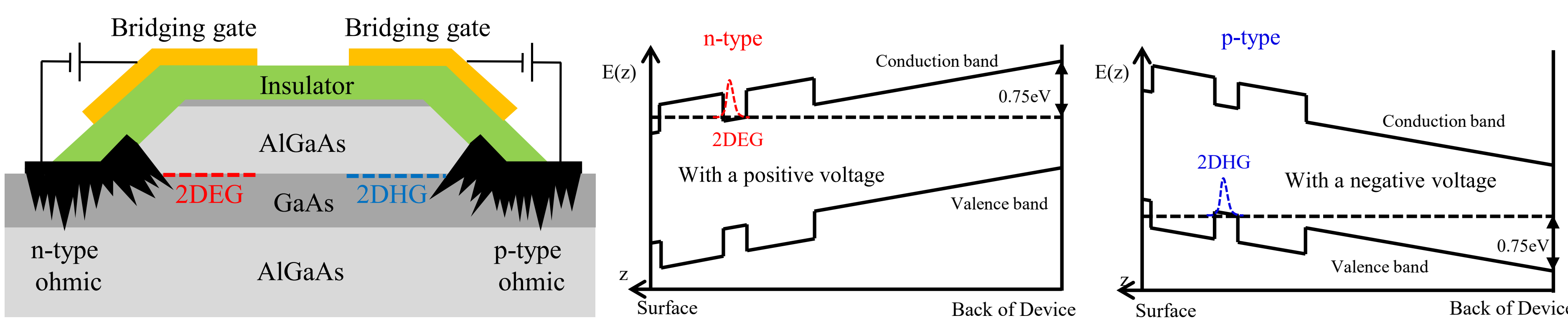
A classical coherent pulse of light	Single-photon source
	
• Two independent (non-correlated) beams	• A quantum superposition of the photon existing

- Can be used to encode quantum information in various ways
- Can be transported over long distances without loss of coherence
- Feature strong quantum correlations for entanglement (can be used in quantum information processing protocols)

Possible single-photon source

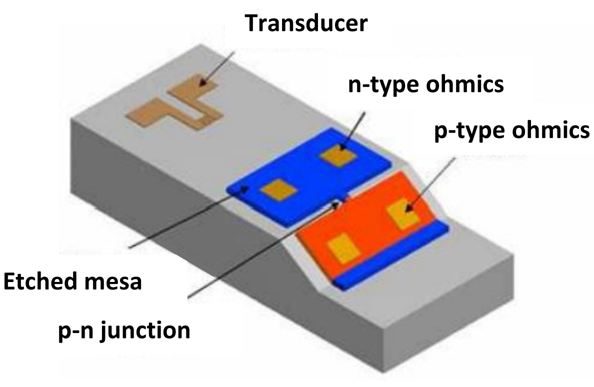


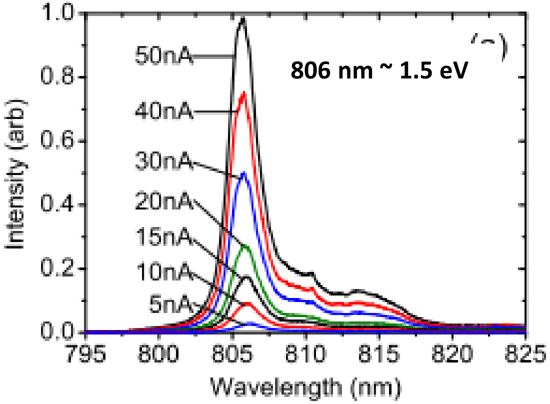
Schematic picture of the SAW-driven single-photon device



Schematic diagram the induced devices

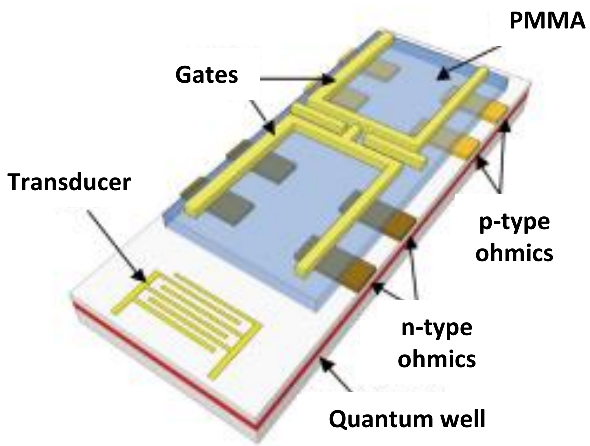
Previous SAW-driven single-photon source

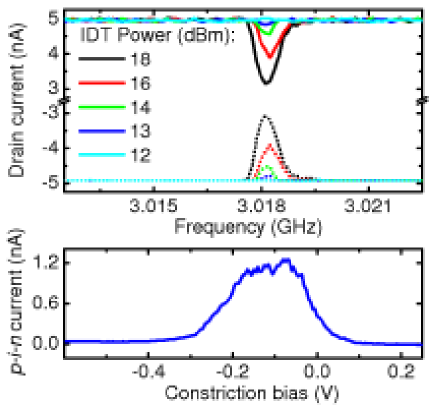




J. R. Gell *et al. Appl. Phys. Lett* (2011)

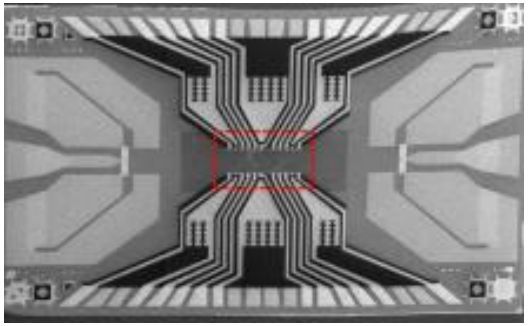
- Demonstrated electroluminescence
- No single-photon evidence
- Difficult of making p-type ohmics

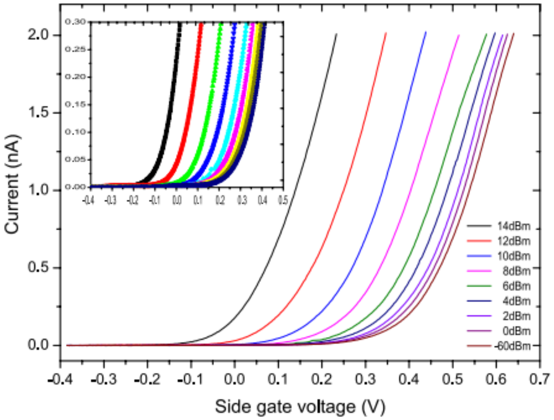




G. De Simoni *et al. Appl. Phys. Lett* (2009)

- Demonstrated electroluminescence
- No single-photon evidence
- Leakage current issue

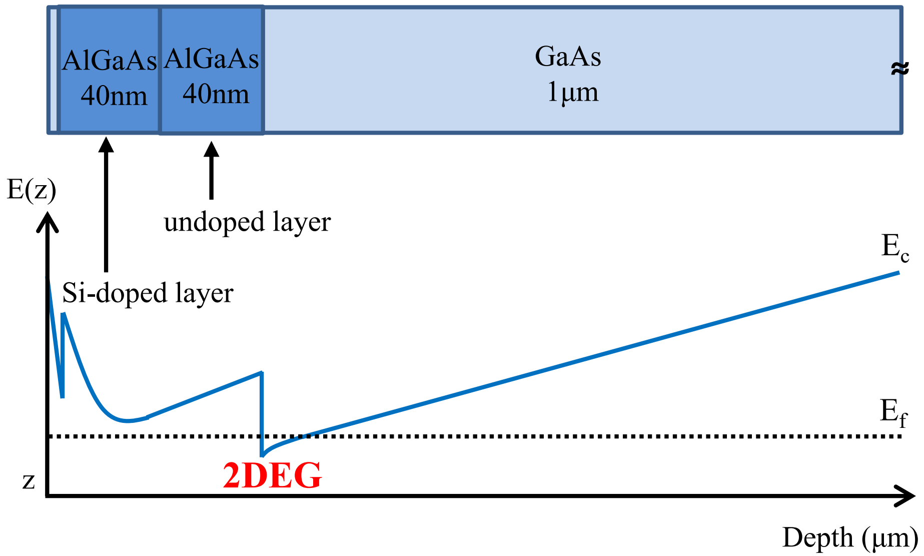




- Demonstrated acoustoelectric current
- No single-photon evidence
- Improved yield of device

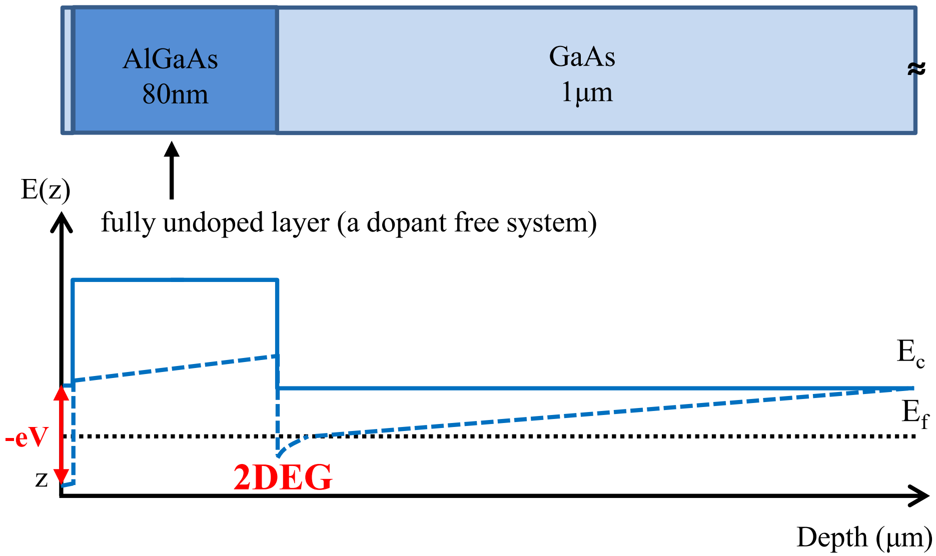
Comparison of two heterostructures

Intentional doping system



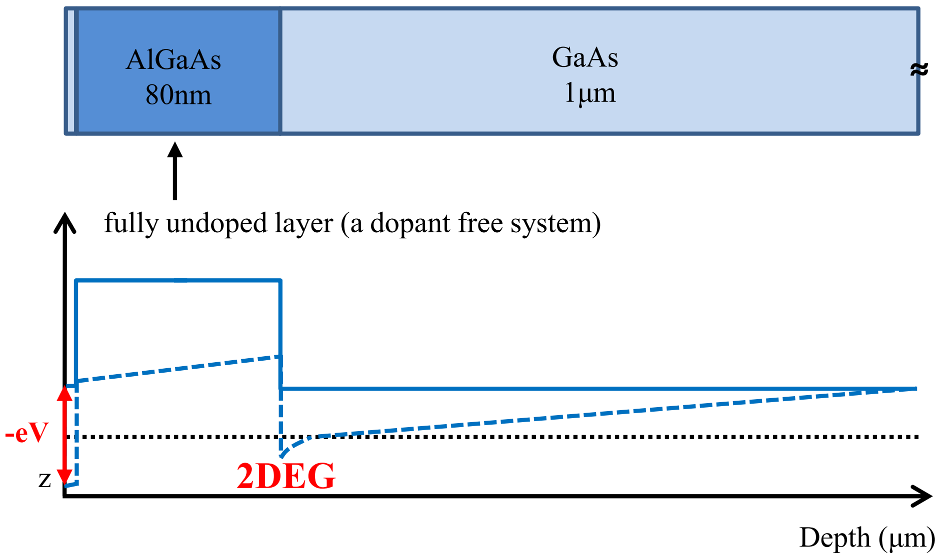
- intentional impurities (dopants) + background impurities
- unipolar type (only n-type or p-type is available)
- carrier density is fixed

Induced system (fully undoped system)

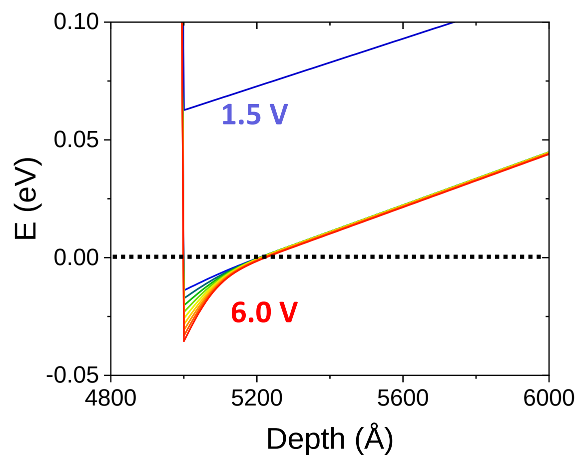


- only background impurities (removal of ionized dopant)
- ambipolar type is available by means of electric field
- carrier density can be controlled

Band bending



- The potential energy is pulled from the surface
- The conduction band of the QW would be dragged
- Pull the QW enough to the Fermi energy
- Start to fill with charge
- The addition of charge to the QW causes the bending of the CB



$$\nabla^2\varphi = -\frac{\rho}{\varepsilon\varepsilon_0}$$

- Solve the one-dimensional Poisson & Schrödinger equations self-consistently
- The CB and VB of the device are symmetric about the Fermi energy

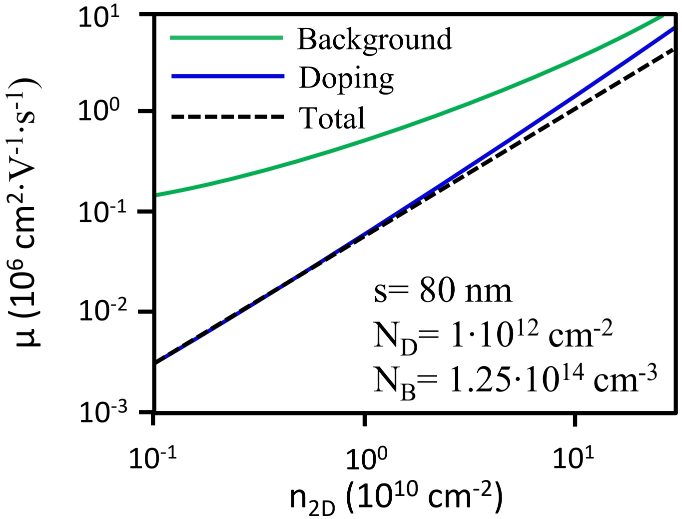
Scattering mechanism

- Matthiessen's Rule: at low temperature the scattering rates given by each individual component can simply be added !

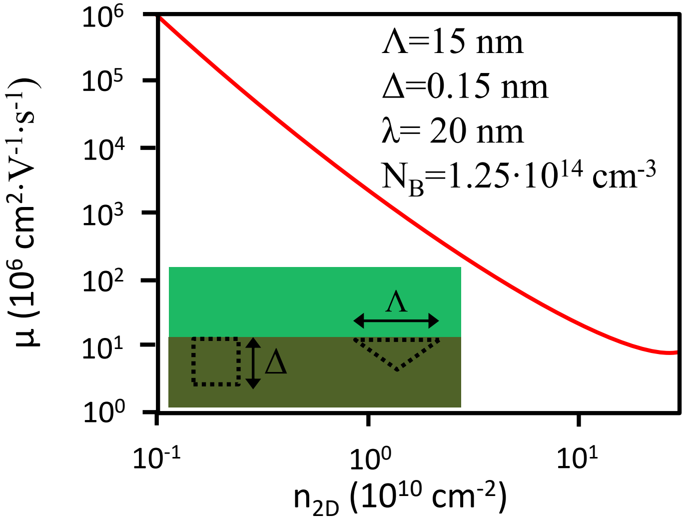
The relaxation time,
$$\frac{1}{\tau} = \frac{1}{\tau_D} + \frac{1}{\tau_B} + \frac{1}{\tau_I} + \frac{1}{\tau_A} + \frac{1}{\tau_{ph}} + \cdots$$

τ_D: due to doping, τ_B: due to background impurities, τ_I: due to interface roughness

τ_A: due to alloy scattering, τ_{ph}: due to phonon scattering

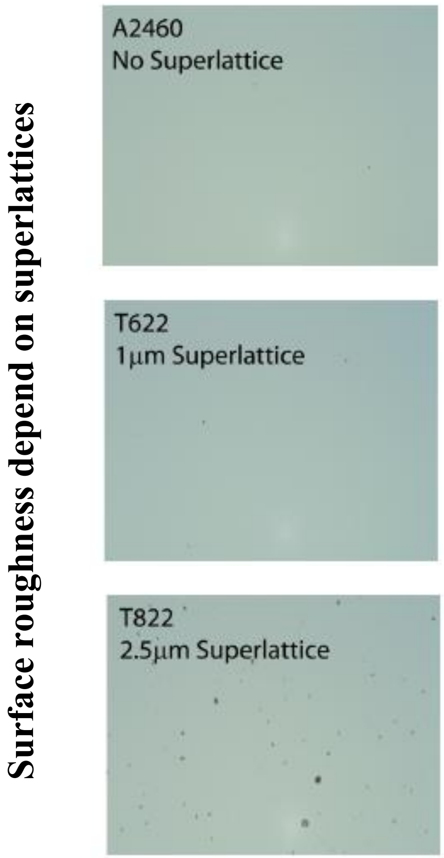


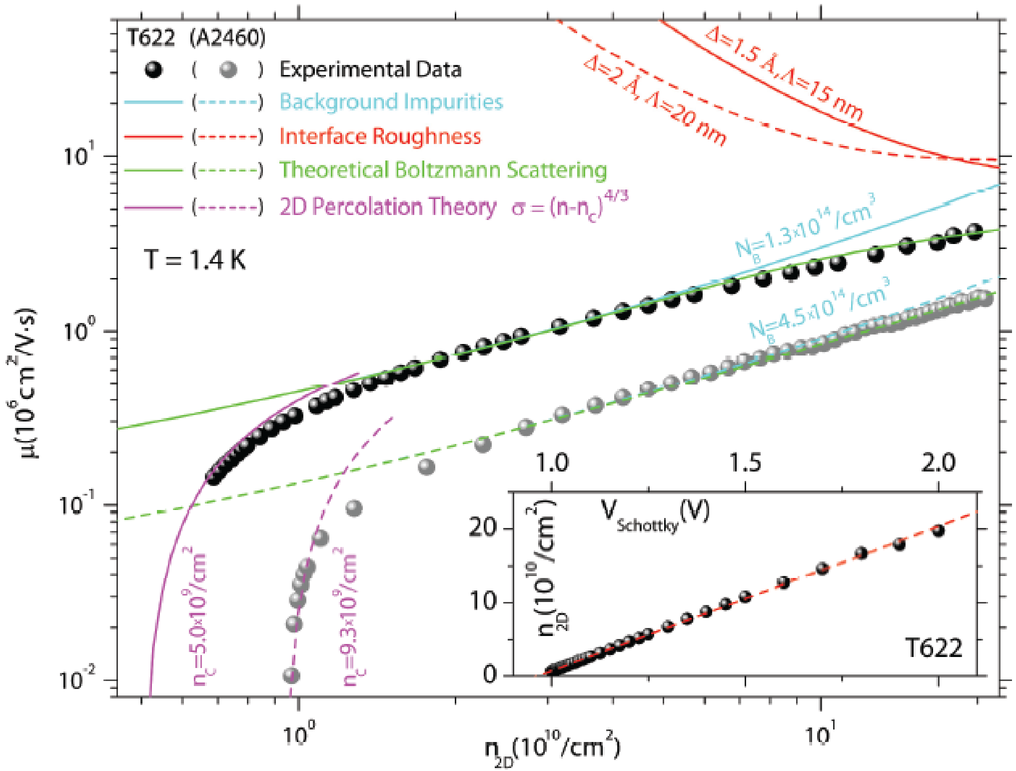
- The limitation to mobility at low carrier density is seen to be completely dominated by the doping.
- From a purely mobility viewpoint, strong motivation for removing intentional dopant from the system.



- Interface roughness parameter is not of high priority.
- Becomes more pronounced at higher densities: extremely important factor when aiming for the highest mobilities.

Minimization of interface roughness

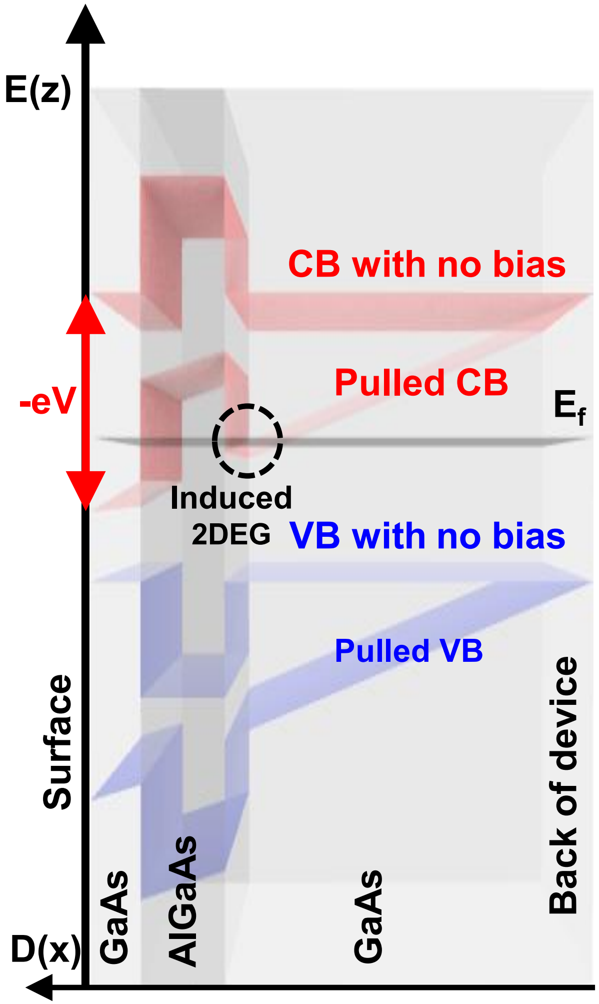


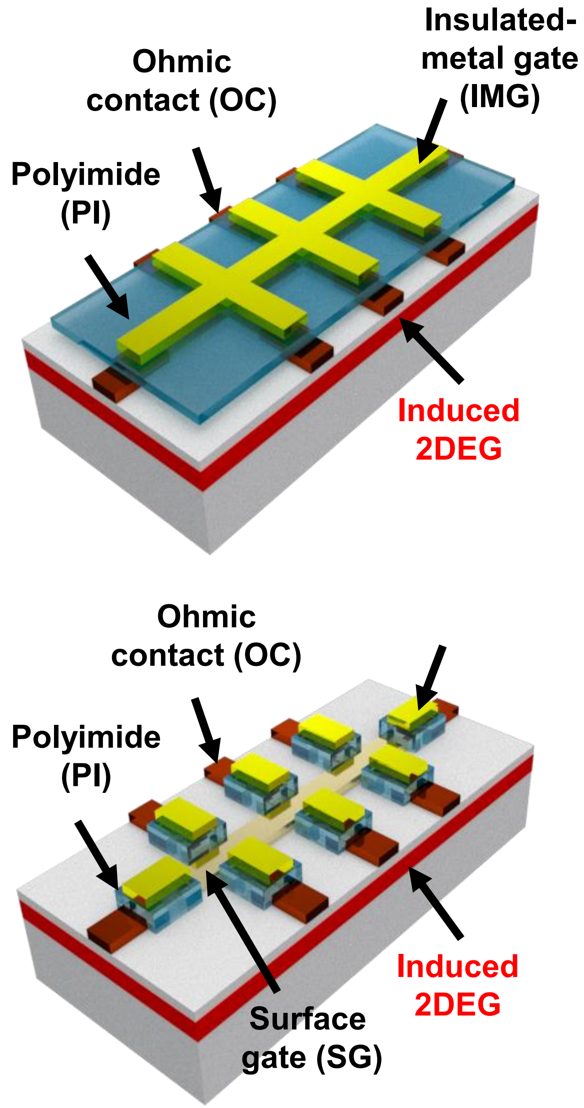


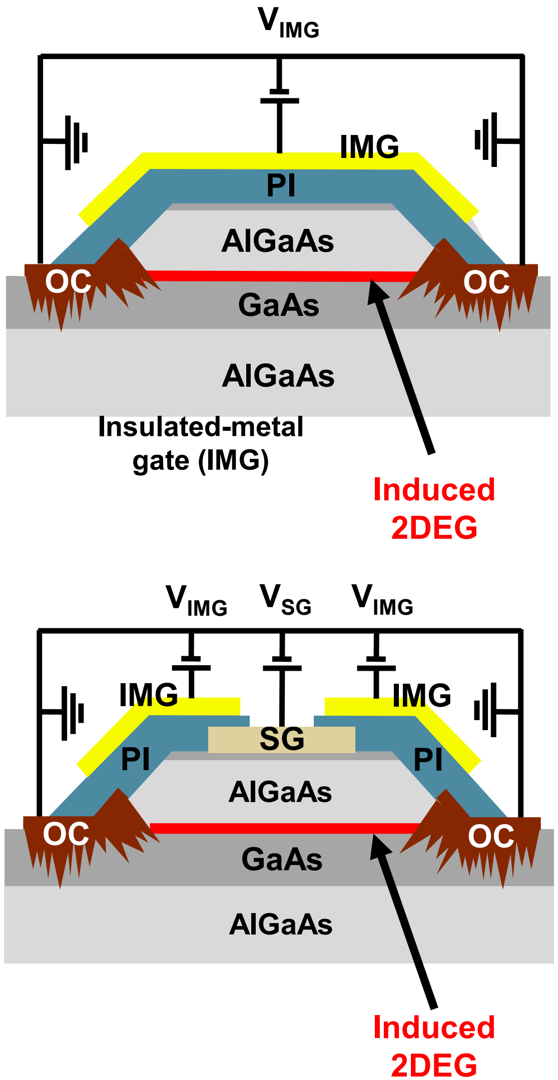
- Superlattices, repeats of very thin GaAs/AlGaAs layers, are thought to prevent defects in the substrate from propagating towards the surface, thus decreasing the interface roughness.

- The mobility falls rapidly because of breakdown of the basic assumptions (electrons can be treated as traveling through a metallic regime): inhomogeneous potential distribution through out the 2D region.

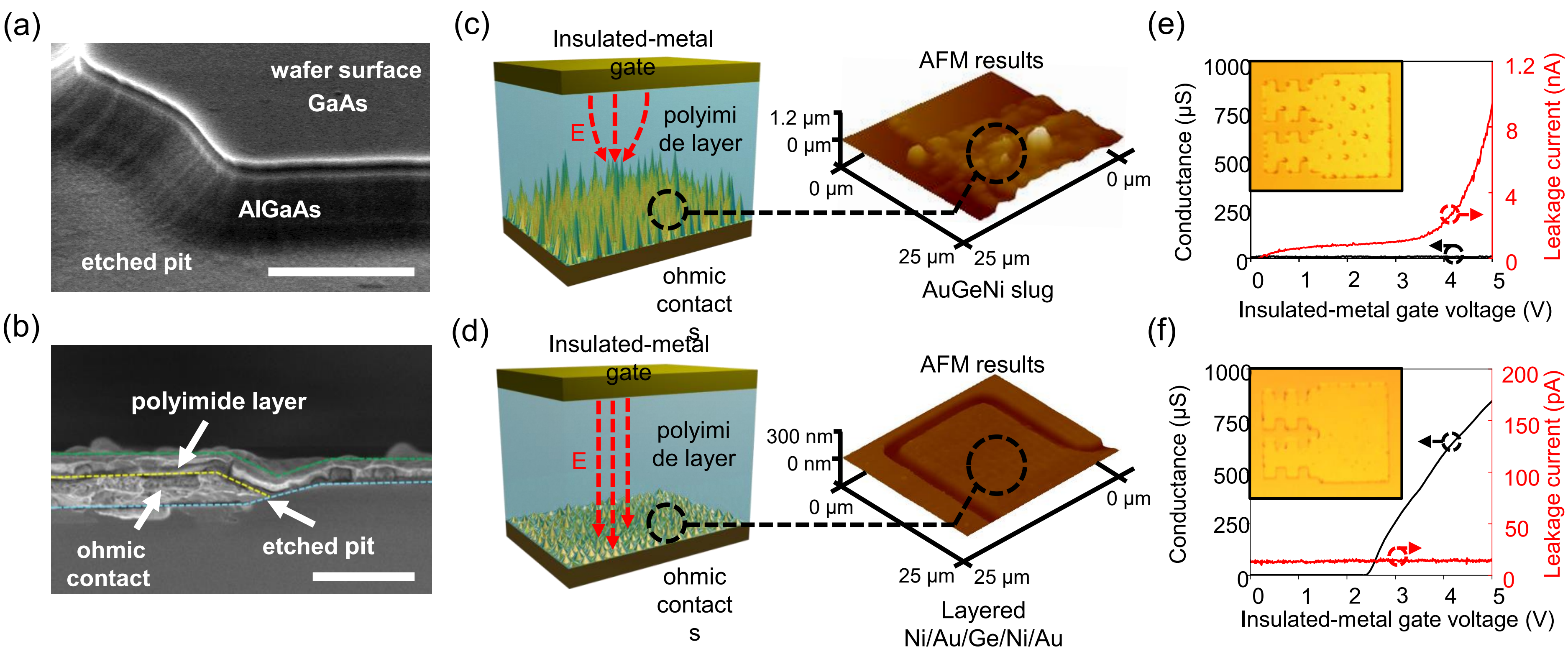
Realization of the induced device



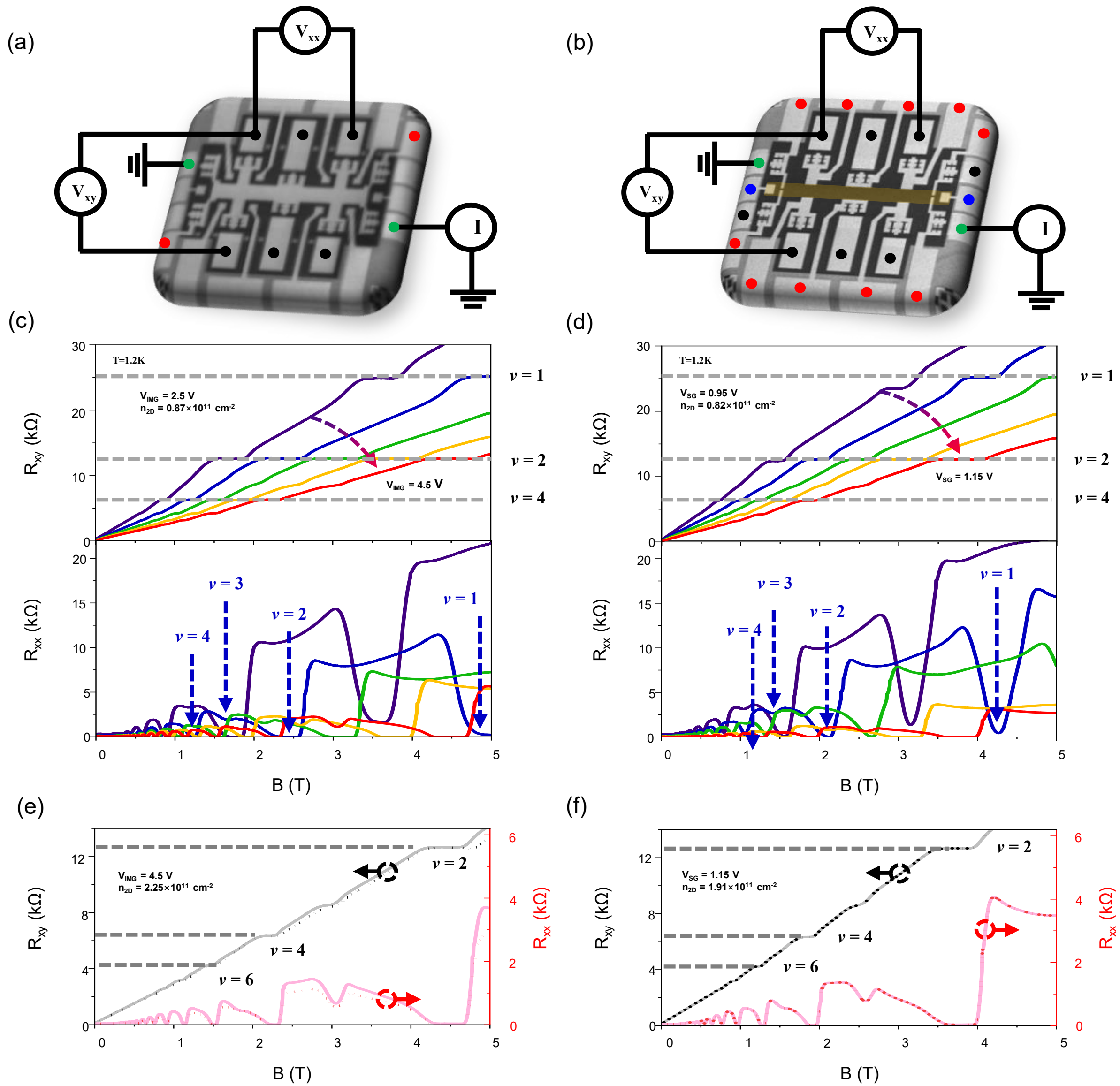




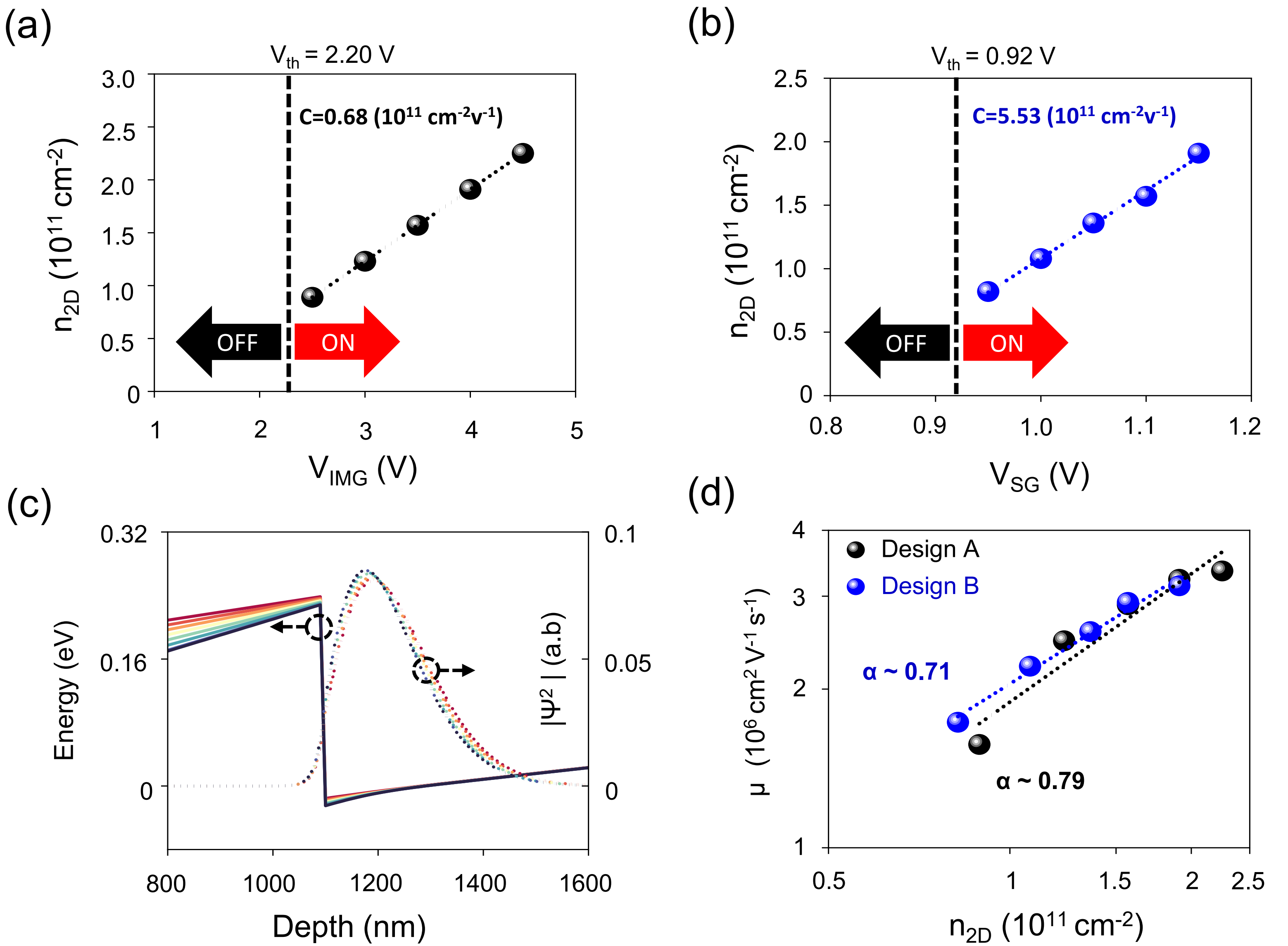
Realization of the induced device



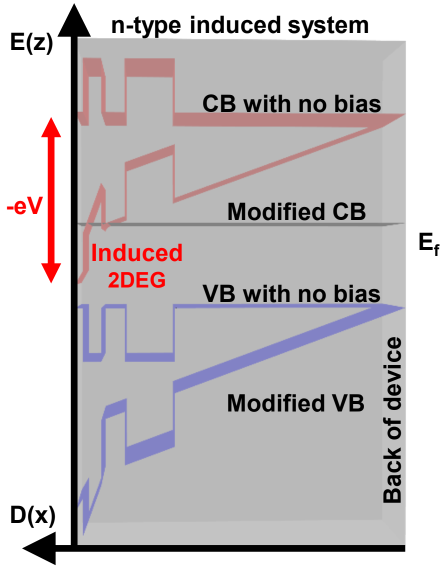
Realization of the induced device

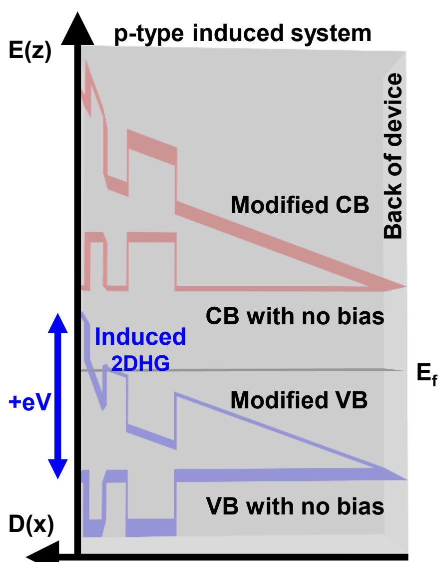


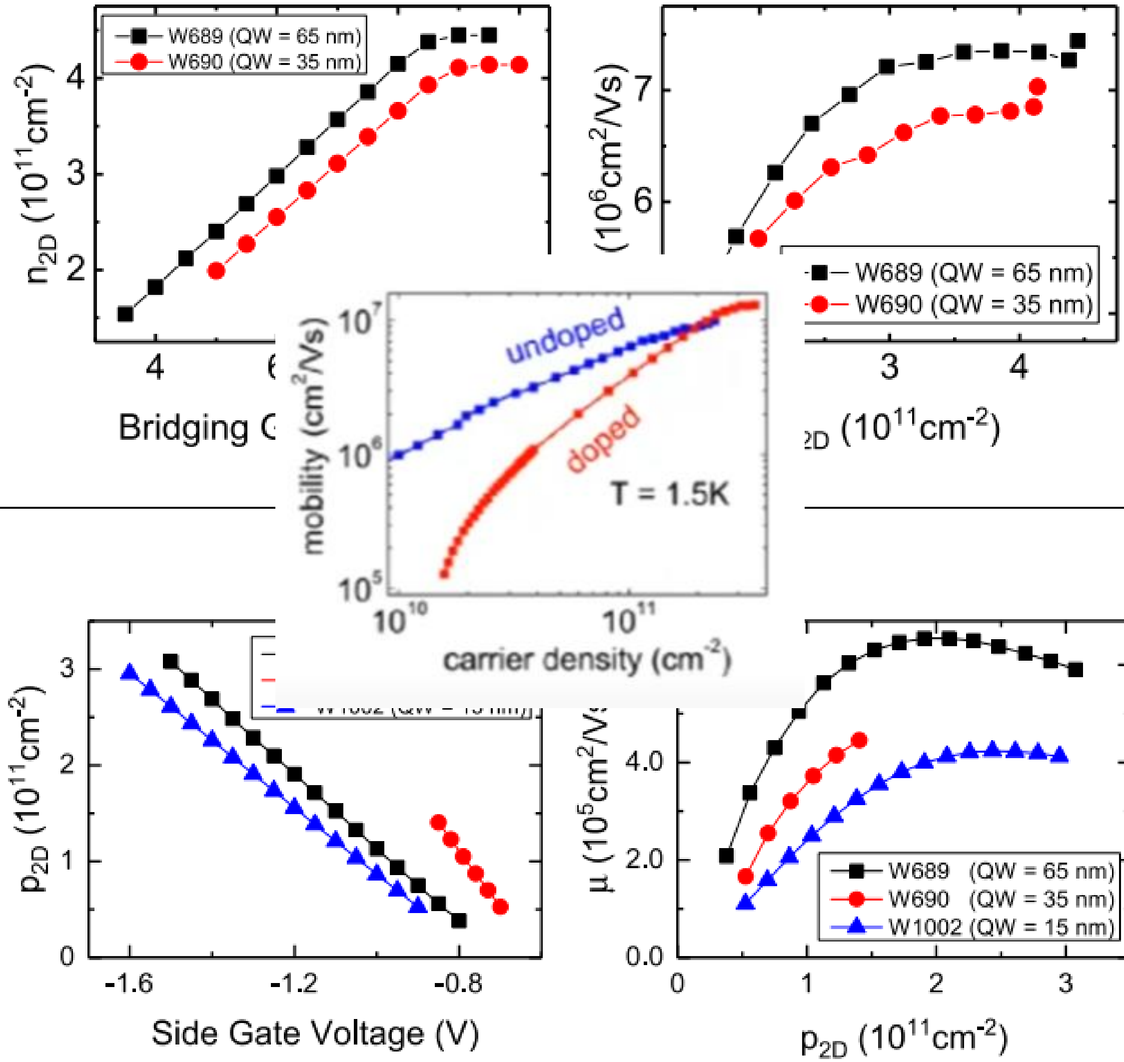
Realization of the induced device



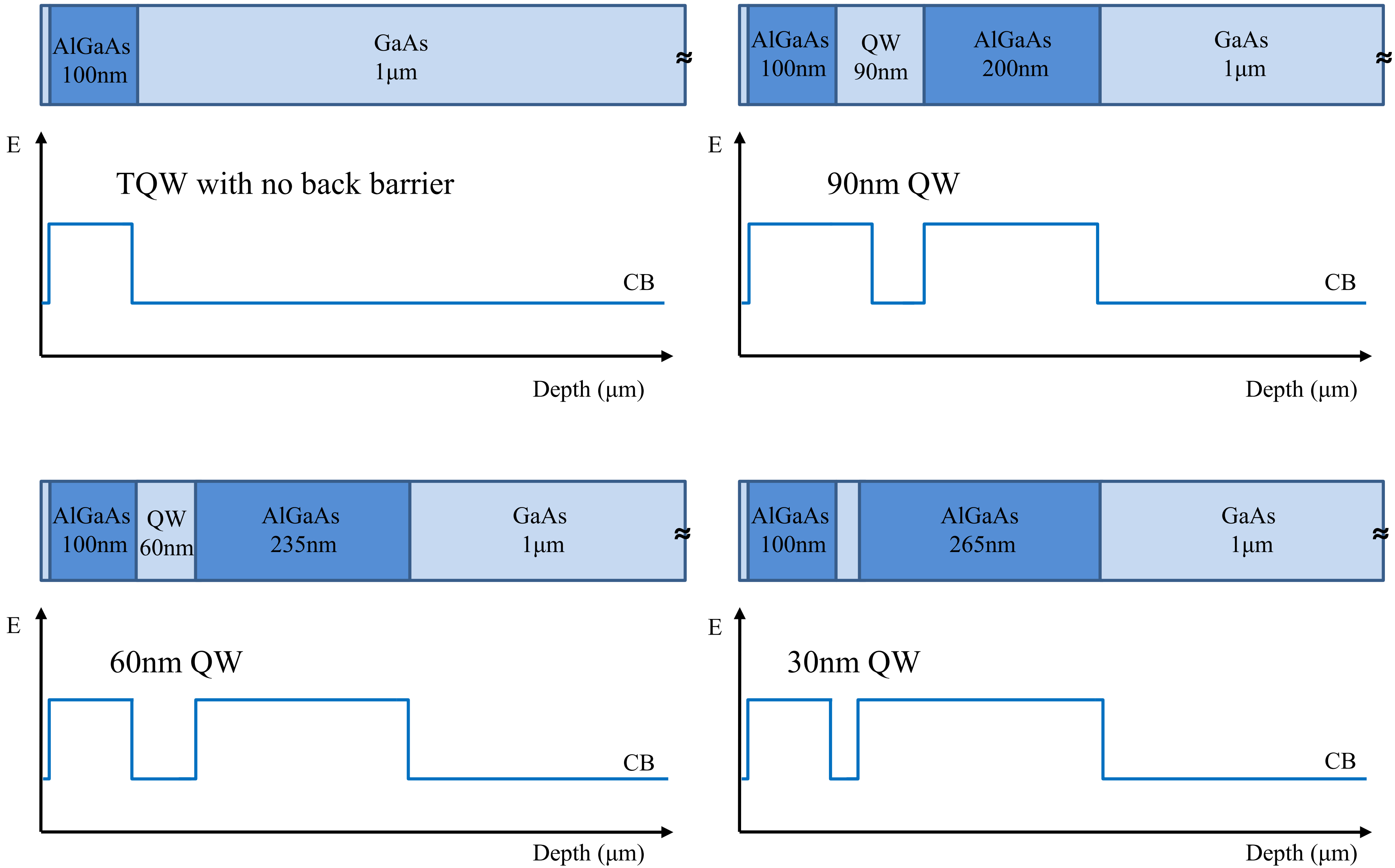
The induced devices



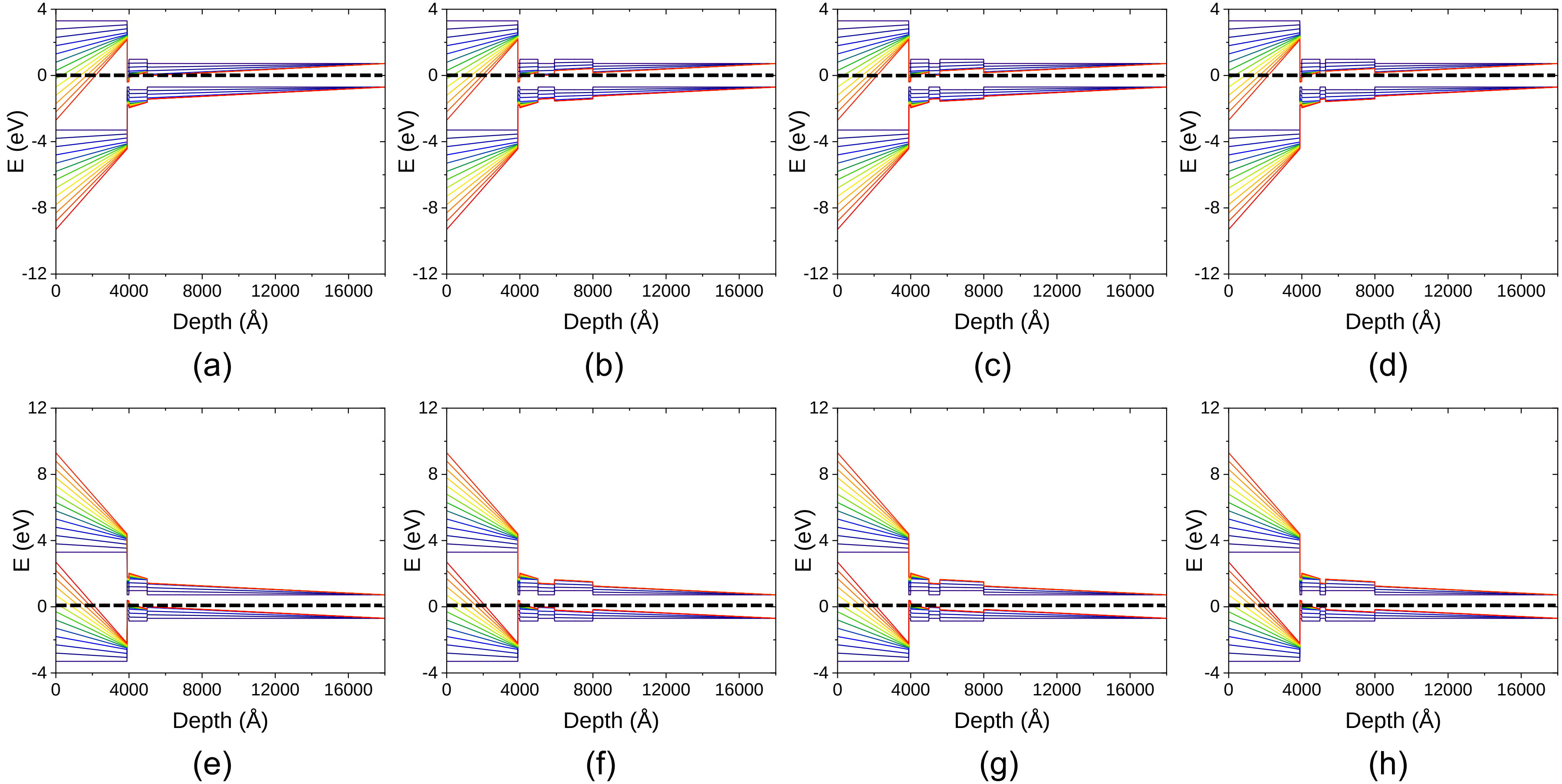




Design of undoped GaAs/AlGaAs wafers

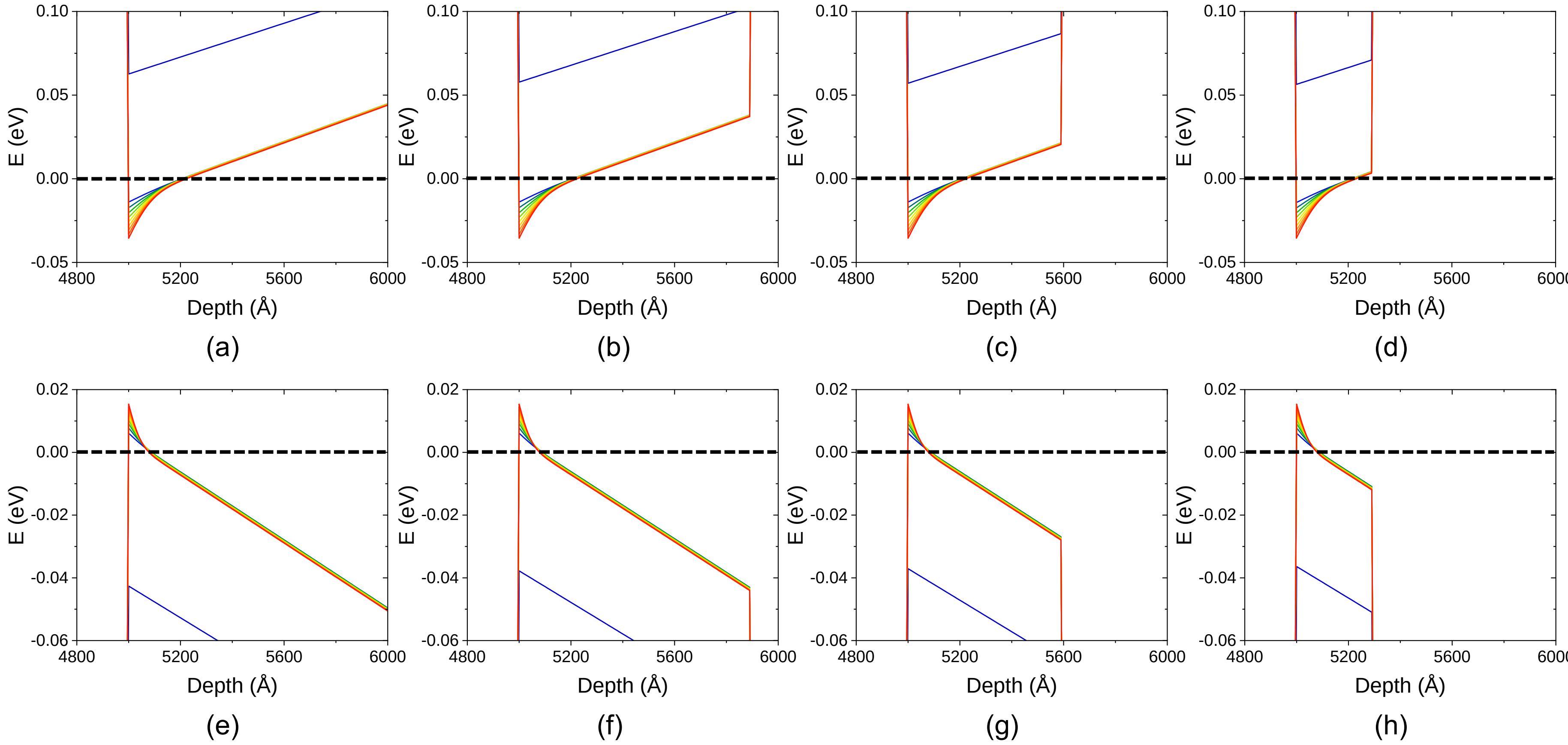


Band structures of the induced system



1D-Poisson and Schrödinger equations calculated self-consistently

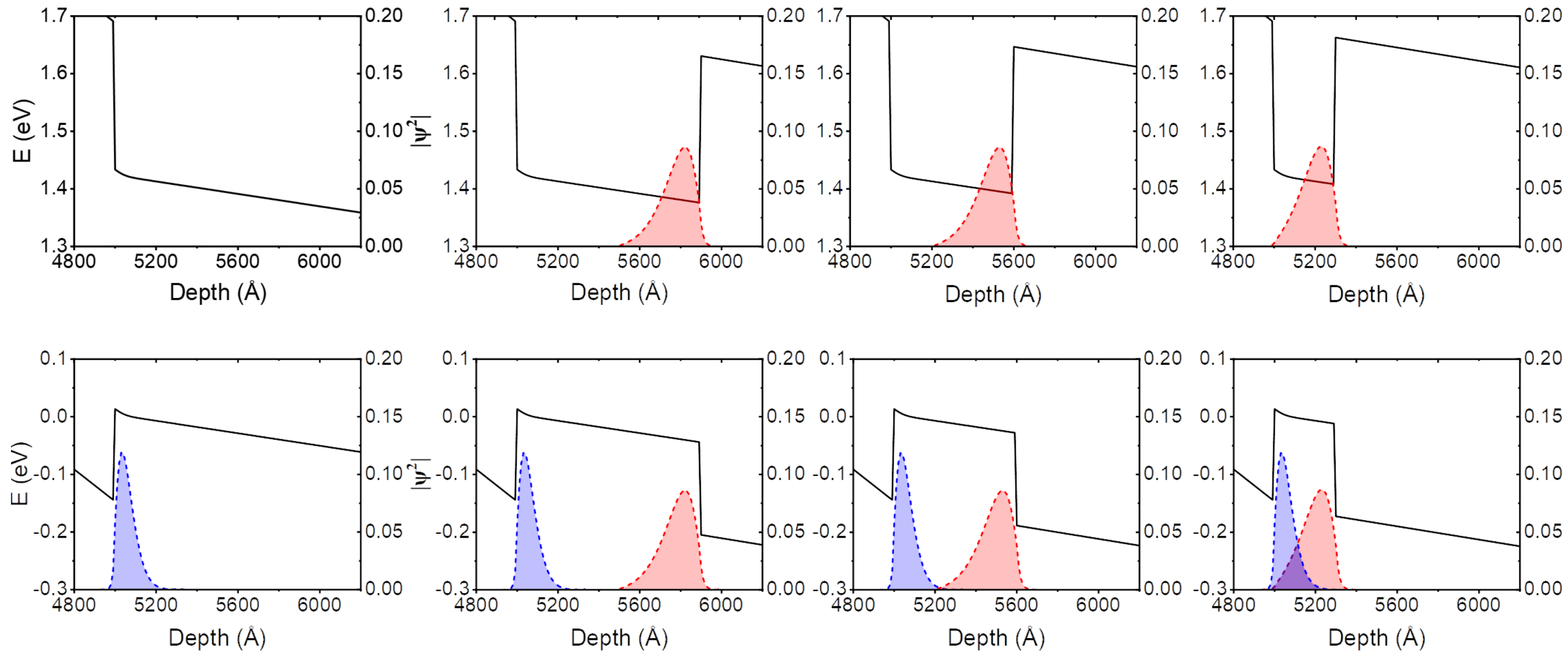
Band structures of the induced system



1D-Poisson and Schrödinger equations calculated self-consistently

Need for confinement of electrons

TQW (no back barrier)	90 nm QW	60 nm QW	30 nm QW

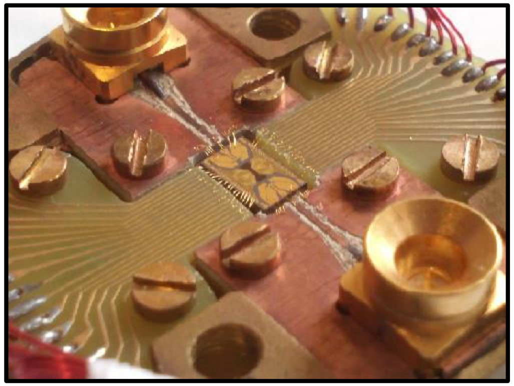


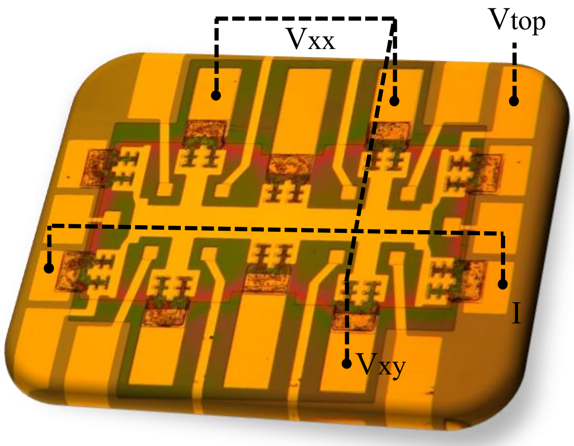
1D-Poisson and Schrödinger equations calculated self-consistently

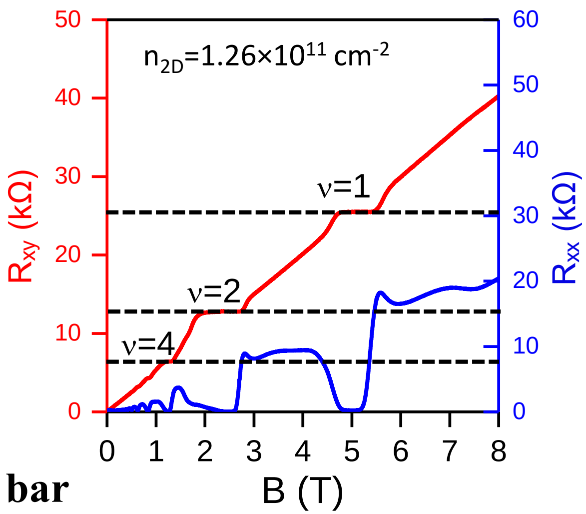
- The aim of this device is making a p-n junction with undoped system for generation of single photons.
- Electrons in an n-type region need to be transported in to a p-type region by SAWs.
- A negative voltage in the p-type region, leading to a negative potential slope: need for narrow QW to confine electrons.

Contents

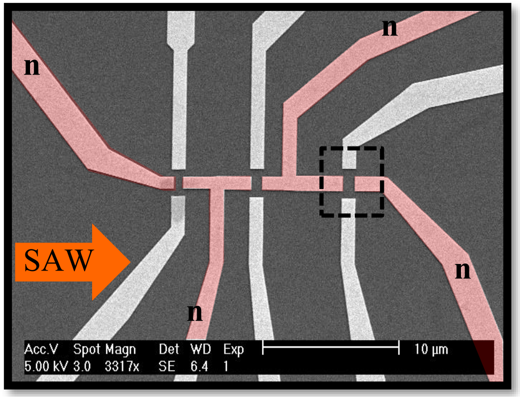
n-type induced system

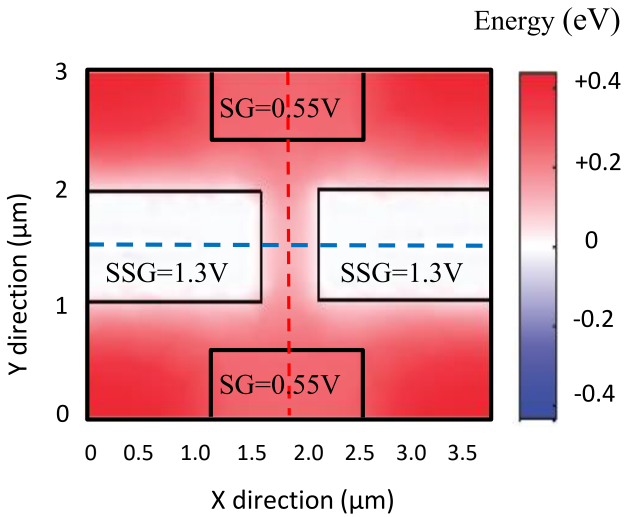


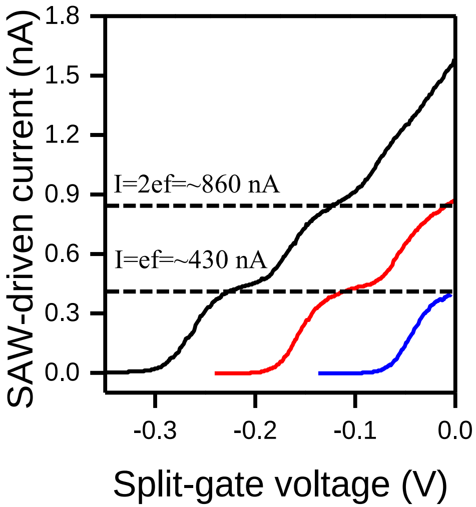




n-type induced device with a Hall bar

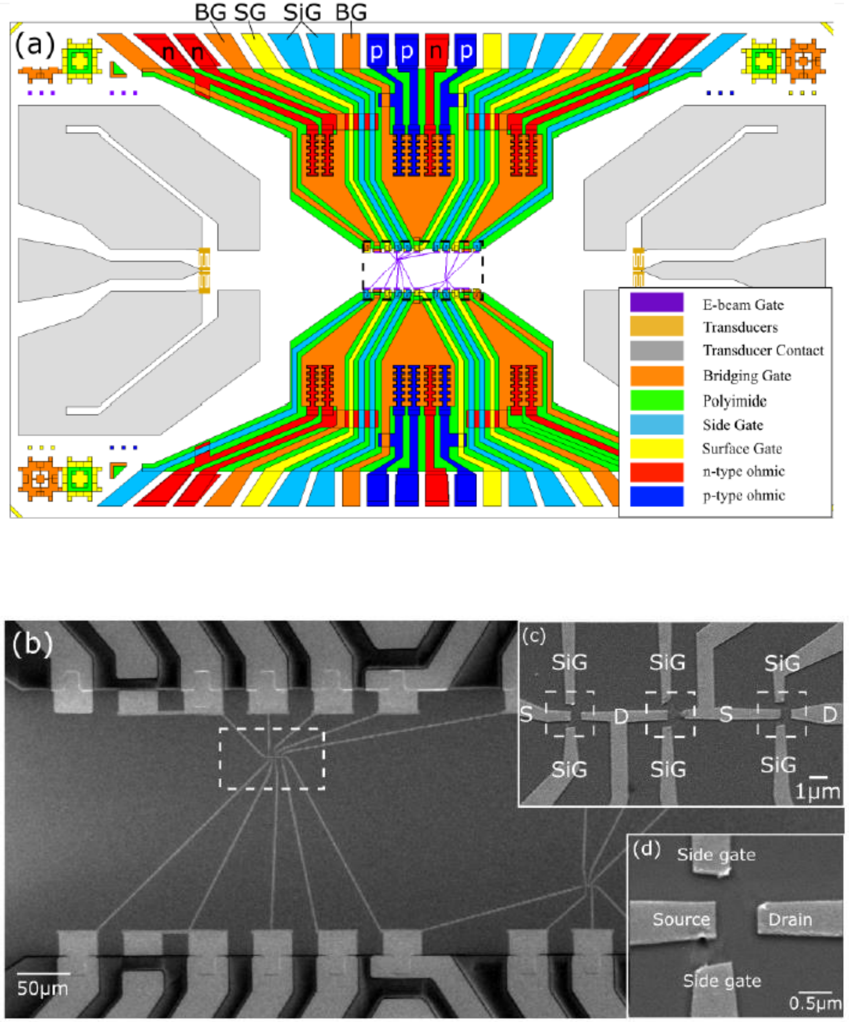


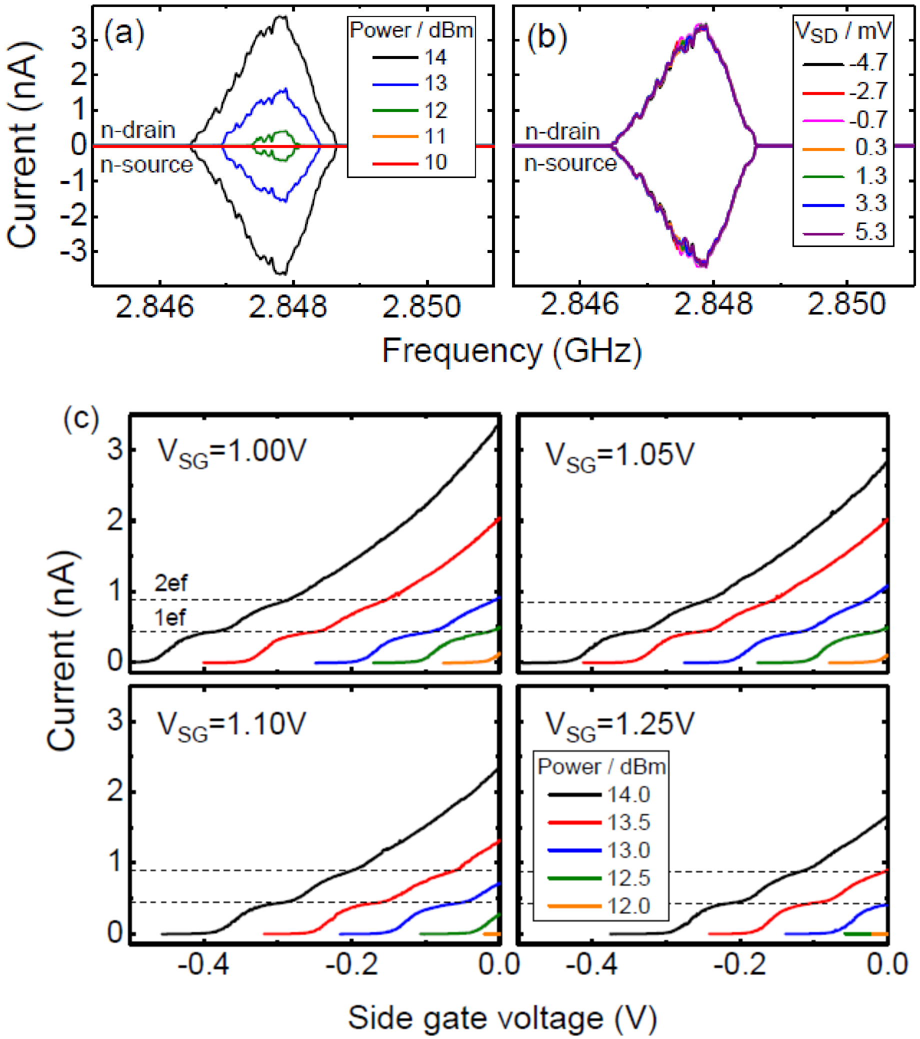




SAW-driven electron transport

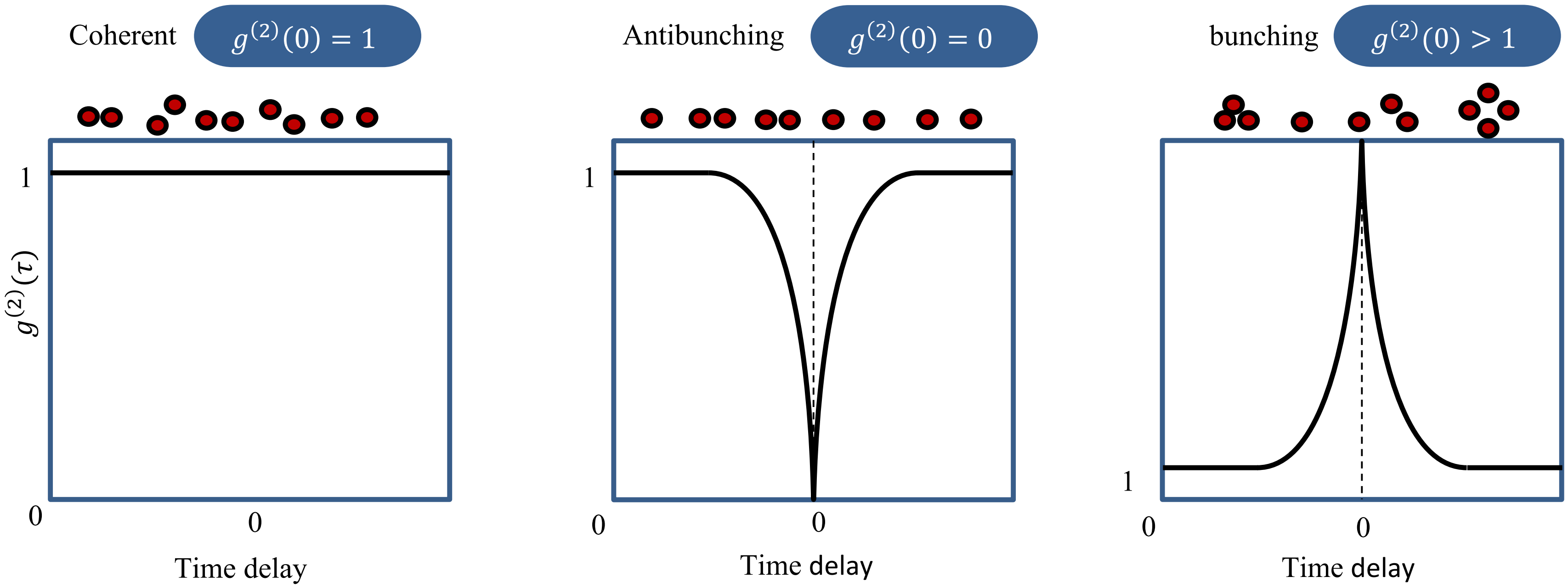
n-type & p-type induced system



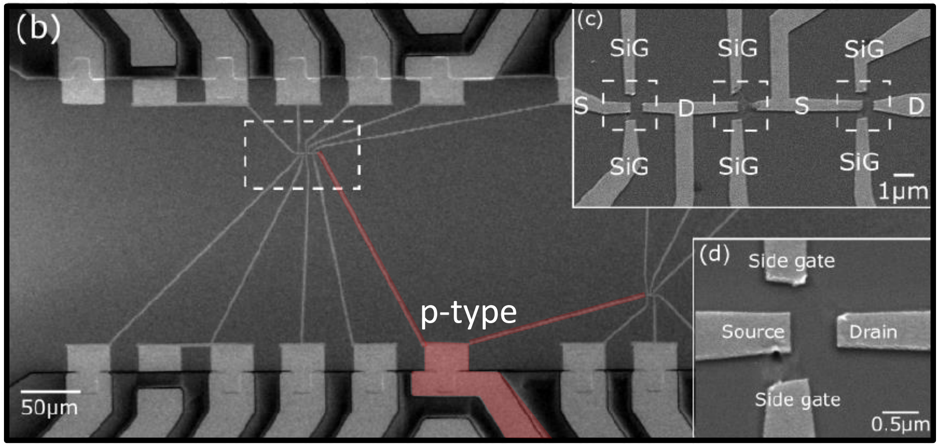


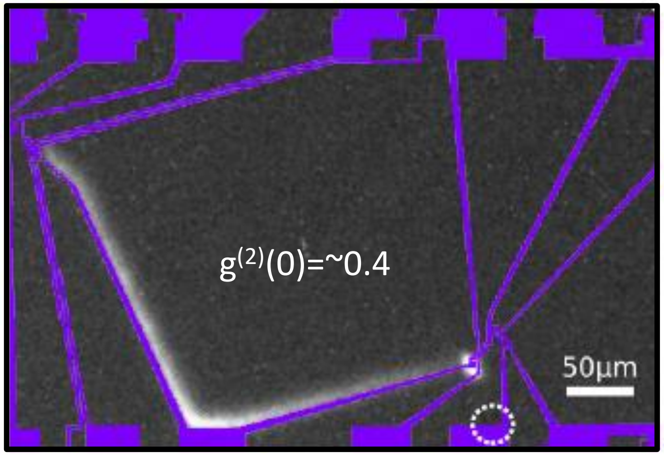
SAW-driven electron transport

n-type & p-type induced system

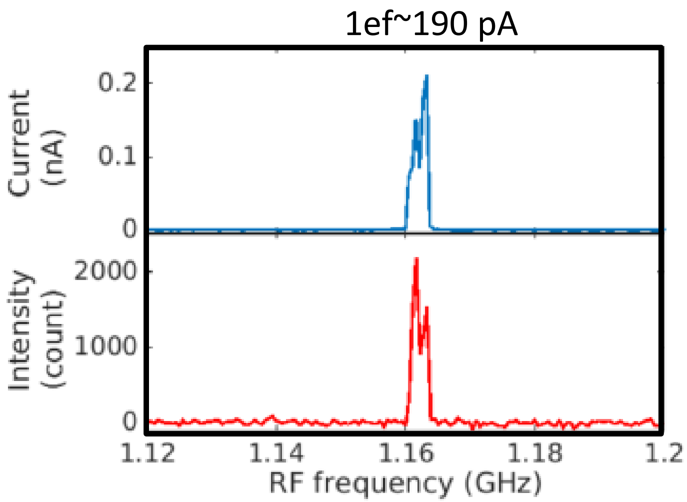


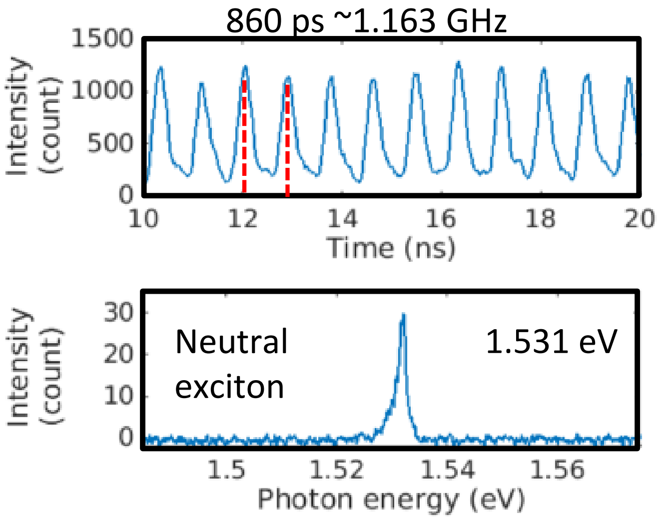
Electron-to-photon qubit conversion





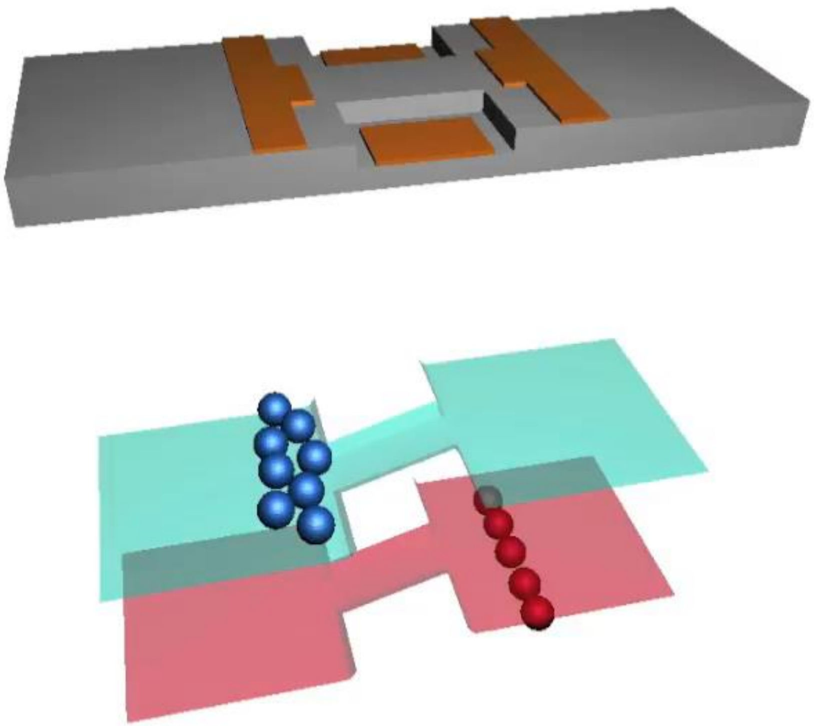
Overall layout of the n-i-p junction SAW device





Electrical and optical properties: electron-to-photon (spin-to-polarization) qubit conversion

Real single-photon process



Thank you for your attention

Conversion between photon and electron qubits

- **Convert electron's spin to circular polarization of a photon**

  - absence of the hole is information that decoheres rapidly

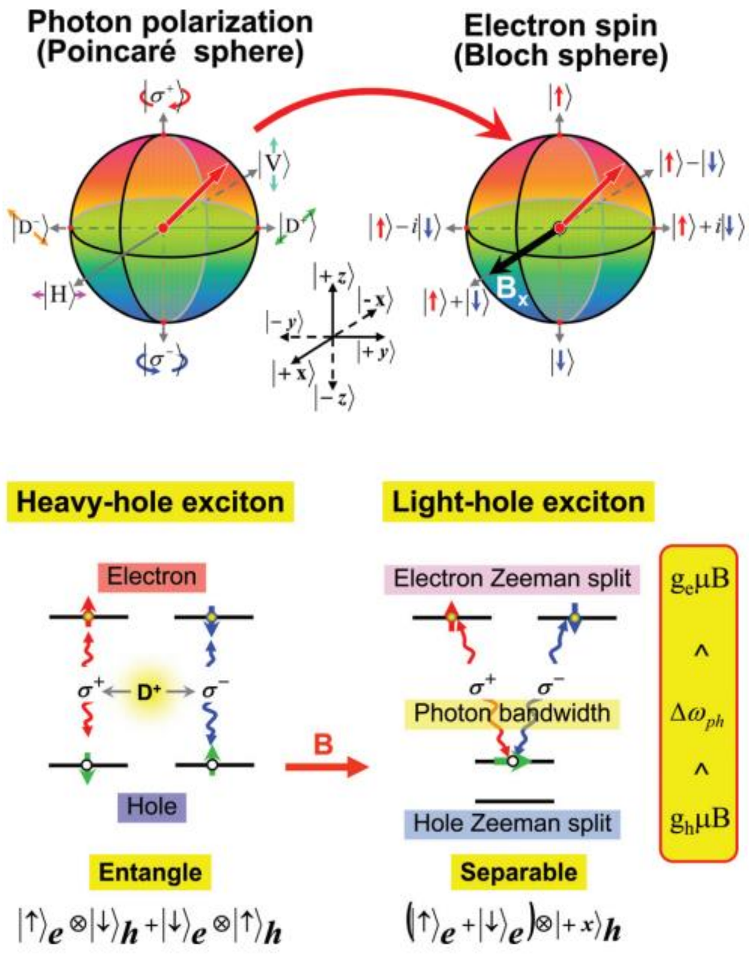
  - so cannot convert a spin qubit (superposition) to photon polarization qubit coherently

- **Kosaka showed that can arrange to have all holes in state $|\rightarrow\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$**

  - any electron in $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$ can recombine with such a hole, photon will maintain the superposition as $\alpha|\sigma^+\rangle + \beta|\sigma^-\rangle$

  - g=0 for electrons (15 nm Al0.14Ga0.86As QW)

  - use the light (not heavy) holes (large enough g)



H. Kosaka, *J. APPL. Phys*. **109**, 102414 (2011), *Nature* **457**, 702 (2009), *PRL* **100**, 096602 (2008)