

Towards single-photon emission by controlled injection of hot electrons across a lateral pn junction

S. Norimoto¹, R. Saxena¹, P. See¹, A. Nasir¹, J. P. Griffiths², C. Chen², D. A. Ritchie², and M. Kataoka¹



¹National Physical Laboratory, Hampton Road, Teddington TW11 0LW, United Kingdom

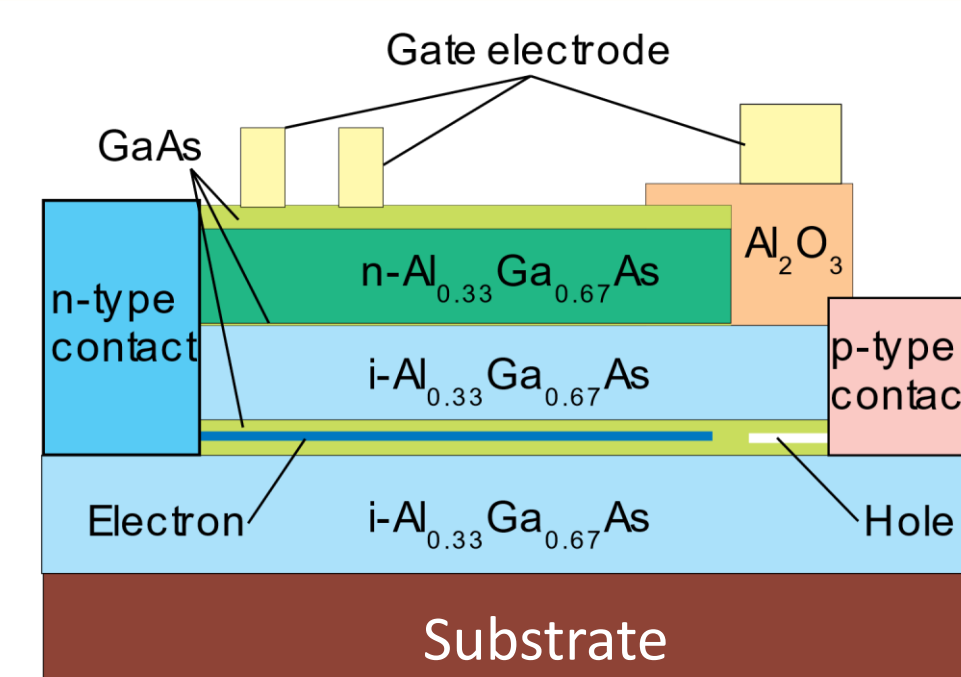


²Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Summary

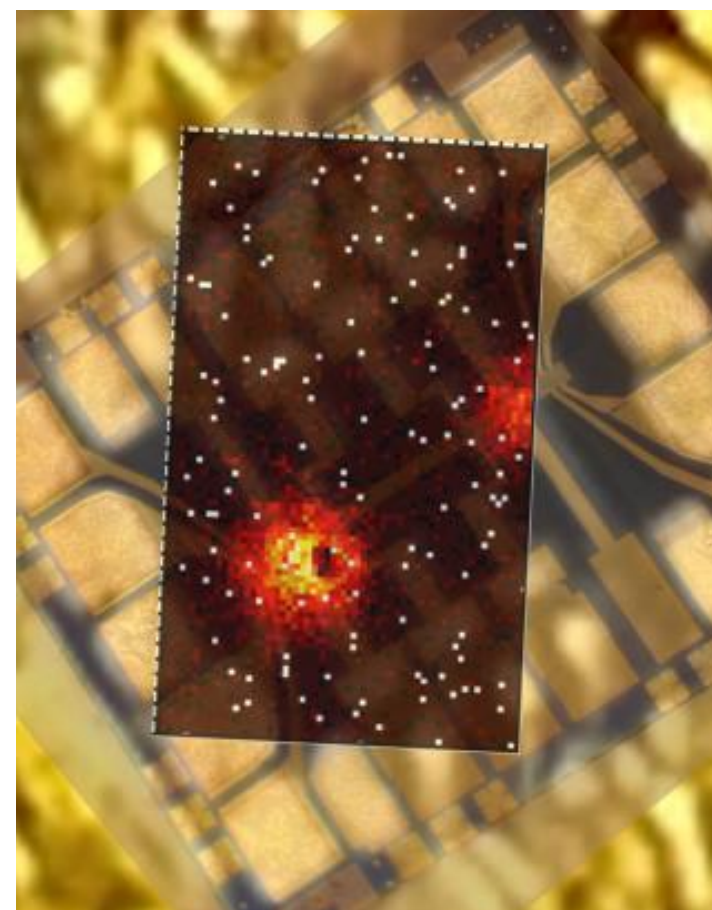
- We demonstrate an experimental method of generating photons from a flow of hot electrons injected across a *pn* junction.
- Samples are created by converting a part of an *n*-type GaAs/AlGaAs quantum well structure into a *p*-type region.
- A mesoscopic potential barrier with a large source-drain bias across is used as a source of hot electrons.
- Hot electrons are transported through edge states formed by Landau levels in the quantum Hall regime.
- Photon emission is observed as hot electrons enter the *p*-type region.
- Magnetic-field dependence of optical spectrum suggests that photons are created by recombination of hot electrons and holes.
- We propose a scheme for clock-controlled single-photon generation by controlled injection of single hot electrons.

Lateral *pn* junction

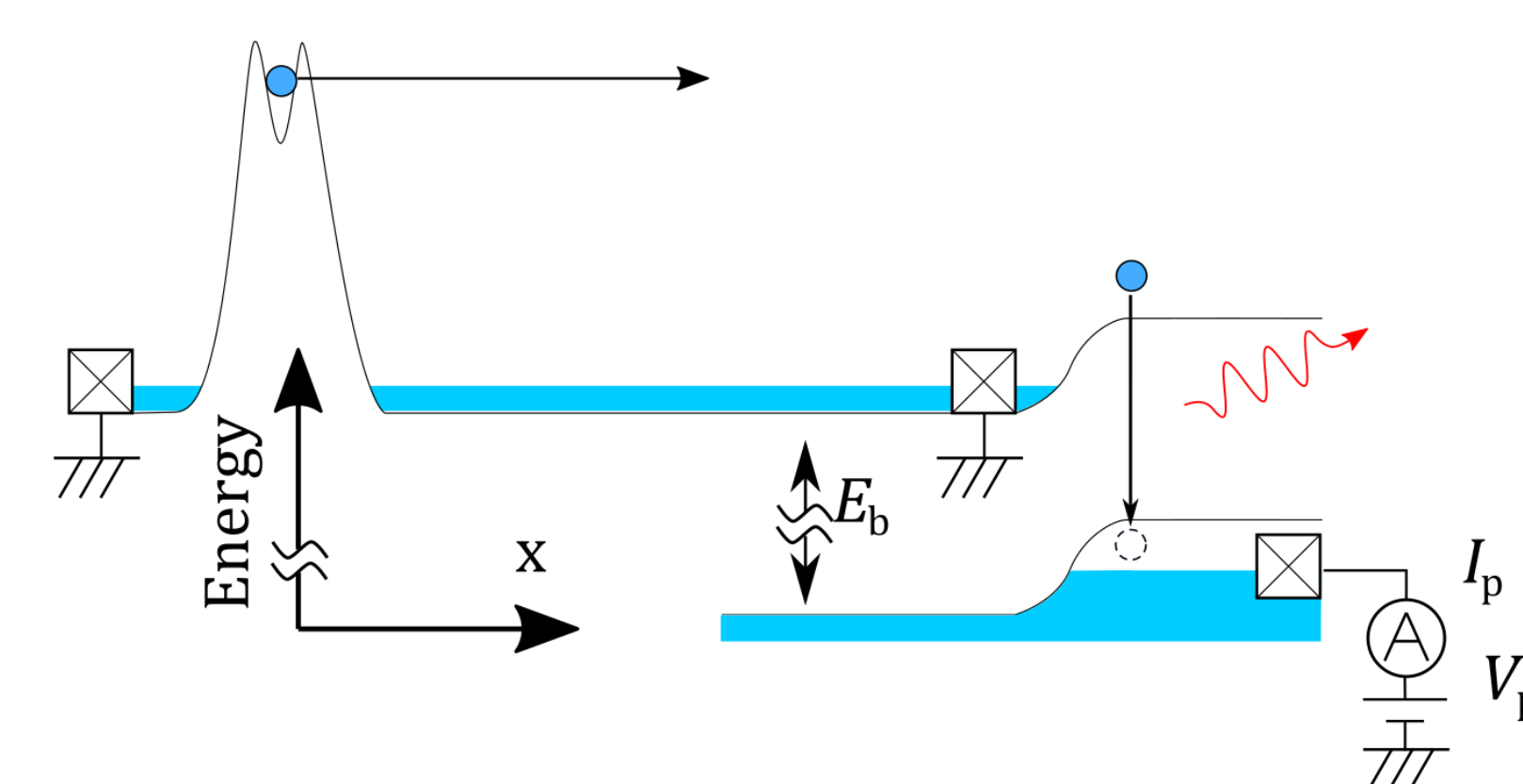


P. Dobney *et al.*, Semicond. Sci. Technol. **38**, 065001 (2023)

- We have developed a method to convert an area of *n*-type GaAs/AlGaAs quantum well heterostructure into *p*-type.
- A doped AlGaAs layer is removed by etching to make the region intrinsic.
- AuBe is deposited and annealed to create *p*-type contacts.
- An insulating layer (Al₂O₃ or cross-linked PMMA) is placed over the etched region.
- A Ti/Au layer is deposited as a gate on the insulator.
- Electroluminescence is observed with a forward bias.



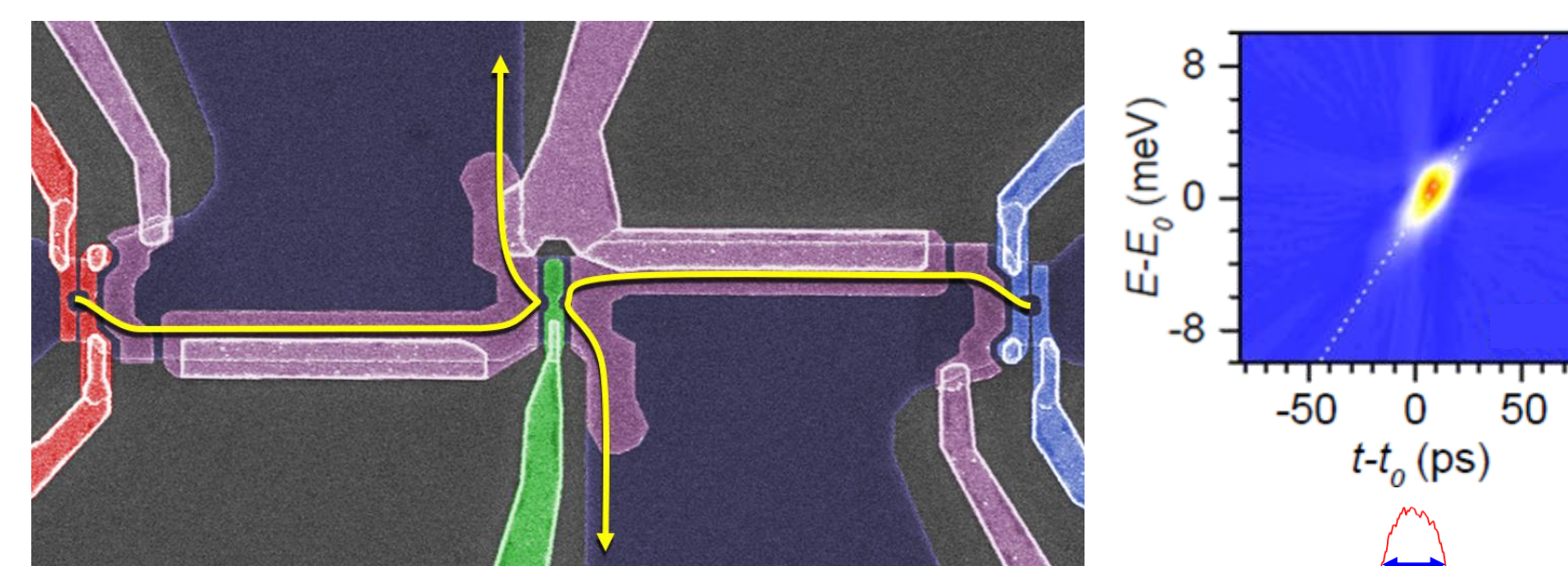
Single-electron to single-photon



S. Norimoto *et al.*, arXiv:2406.04556 (2024)

- Our proposed single-photon-source device consists of a single-electron pump and a lateral *pn* junction.
- The drain side of the pump is grounded through an *n*-type ohmic contact.
- The junction bias is set below its threshold so that thermally-excited electrons in the Fermi sea cannot move across the junction.
- One electron is emitted from the electron pump on demand.
- The hot electron is channelled towards the *pn* junction through an electron waveguide (e.g. quantum Hall edge states).
- Energy relaxation of the emitted hot electron needs to be suppressed (e.g. by controlling the edge potential).
- When the hot electron enters the *p*-type region, it recombines with a hole to create a photon.

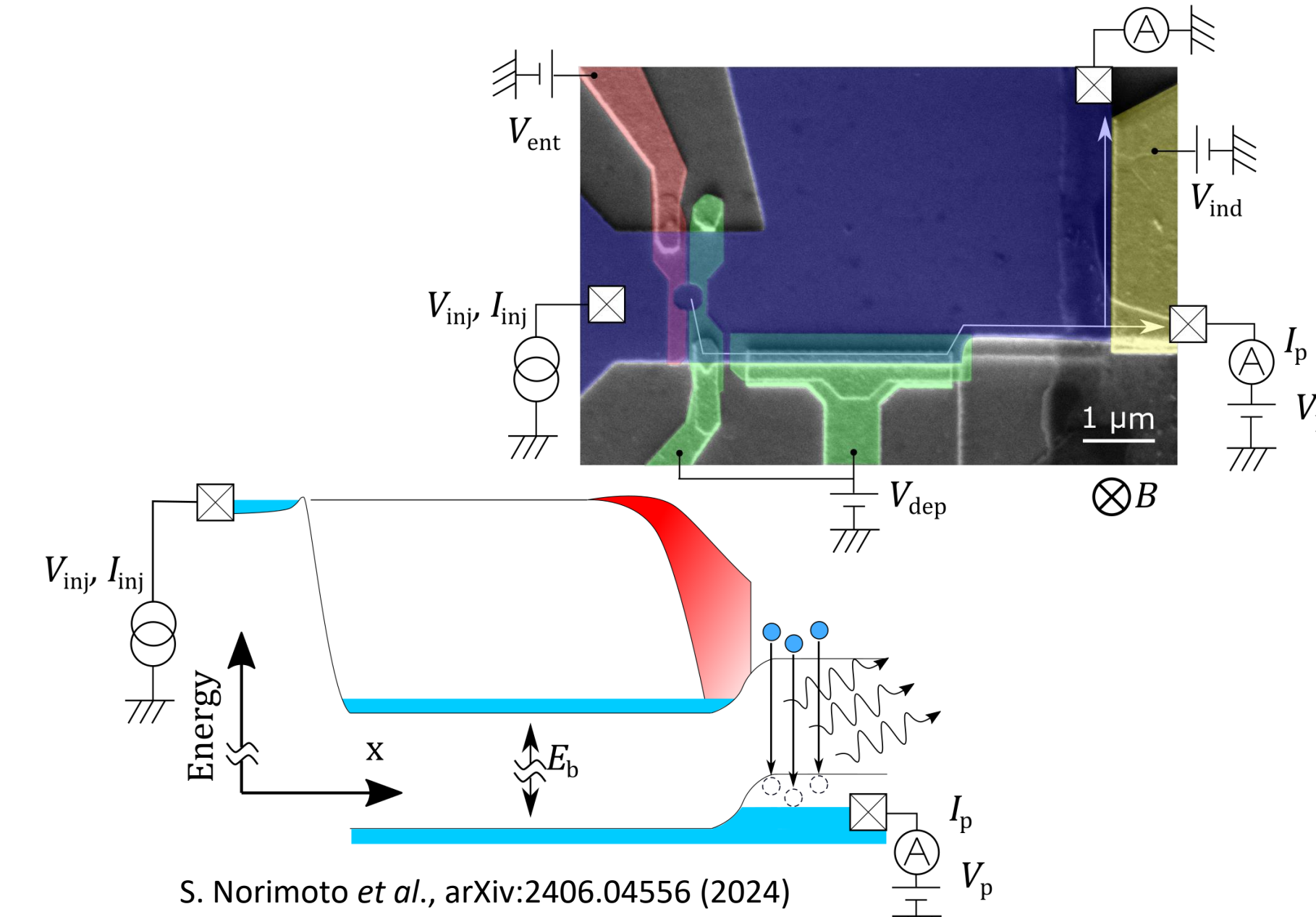
Electron quantum optics



e.g. J. D. Fletcher *et al.*, Nature Nanotechnology **18**, 727 (2023)

- Experimental methods have been developed to control and detect travelling electrons at the picosecond timescale.
- Our single-photon sources could be used to transfer information from electrons to photons.
- Also, they could be used as single-shot single-electron detectors.

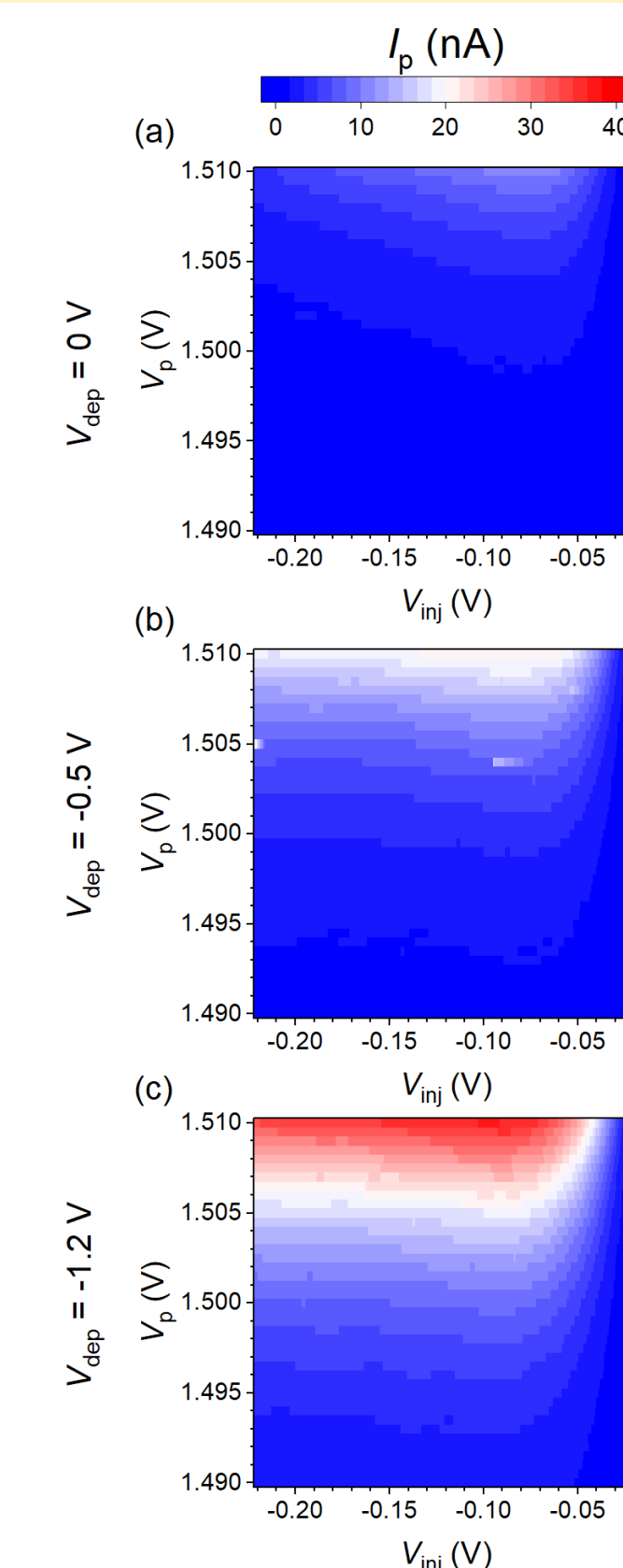
Hot-electron injection device



S. Norimoto *et al.*, arXiv:2406.04556 (2024)

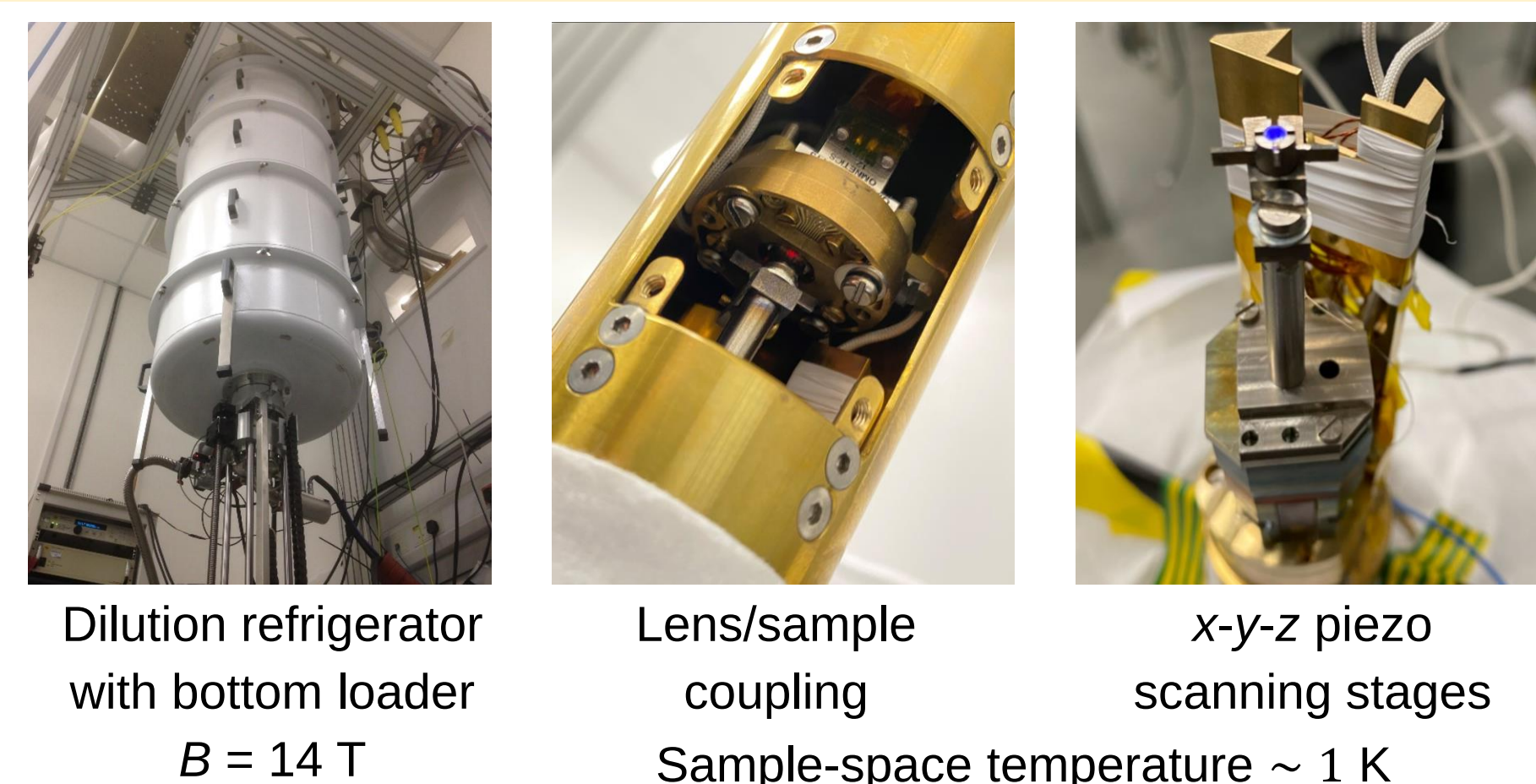
- V_{inj} is applied to the source contact to emit hot electrons over a mesoscopic barrier defined by a surface gate (red) into the drain (sink) region of the two-dimensional electron gas.
- A large magnetic field ($|B| \sim 10$ T) is applied to channel the electrons along the edge of mesa, where the edge-depletion gates (green) are used to suppress the energy relaxation.
- A *p*-type region is created by inducing holes with an applied voltage V_{ind} on the inducing gate (yellow).
- A *pn* junction forward bias V_p is set at ≥ 20 mV below the threshold (1.535 V at $|B| = 10$ T in our device).
- Only the electrons that maintain their energy above the energy step at the *pn* junction enter the *p*-type region and emit photons.

Hot-electron injection current

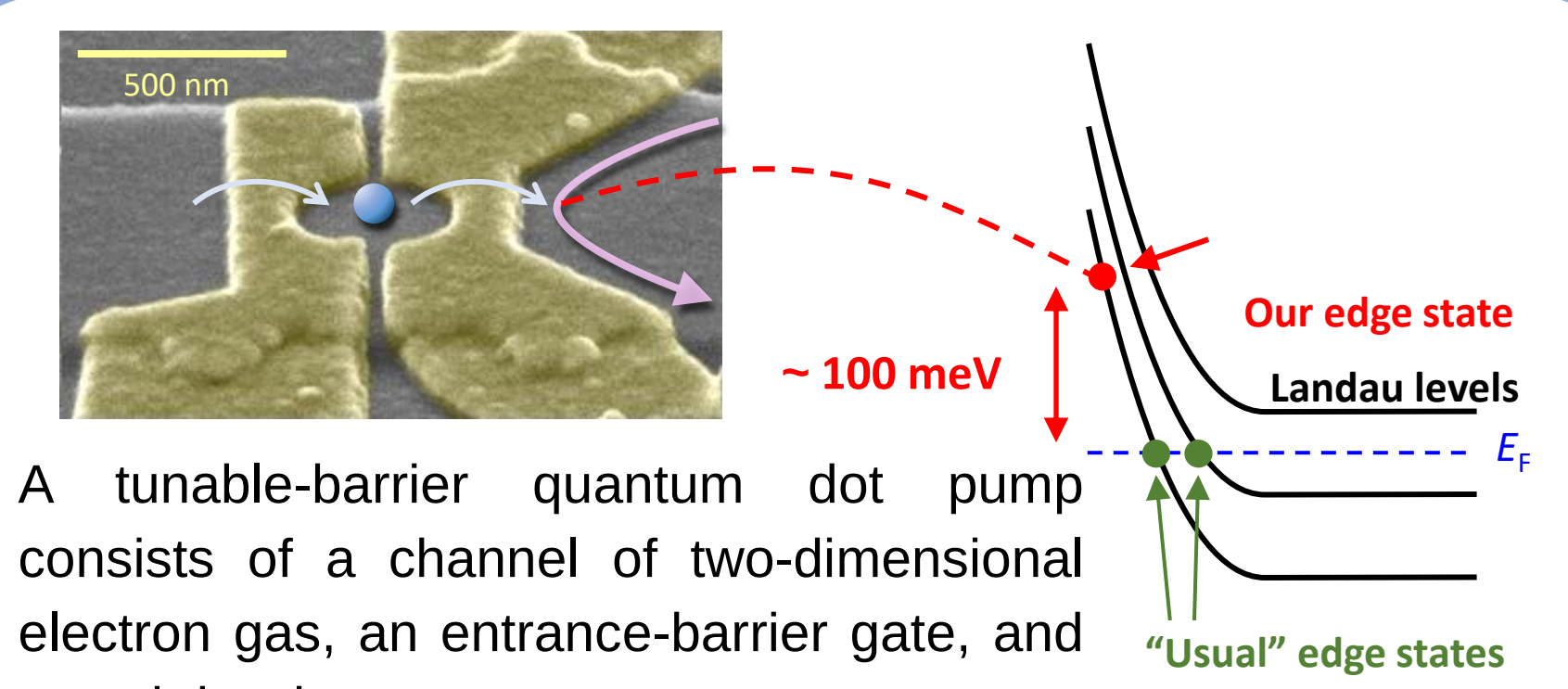


- The plots on the left show the current I_p injected across the *pn* junction in colour. (Data taken at $B = -10$ T.)
- The vertical axis is the forward bias applied across the *pn* junction. The *pn* junction threshold was 1.535 V, hence the junction was under-biased in the range shown.
- The horizontal axis is the injection bias V_{inj} for hot electrons at the source. The barrier height was adjusted to keep the injection current constant at $I_{inj} = 300$ nA.
- The voltage V_{dep} on the edge depletion gates are varied between the plots.
- As V_{dep} increases (negatively), the hot-electron current across the *pn* junction increases.

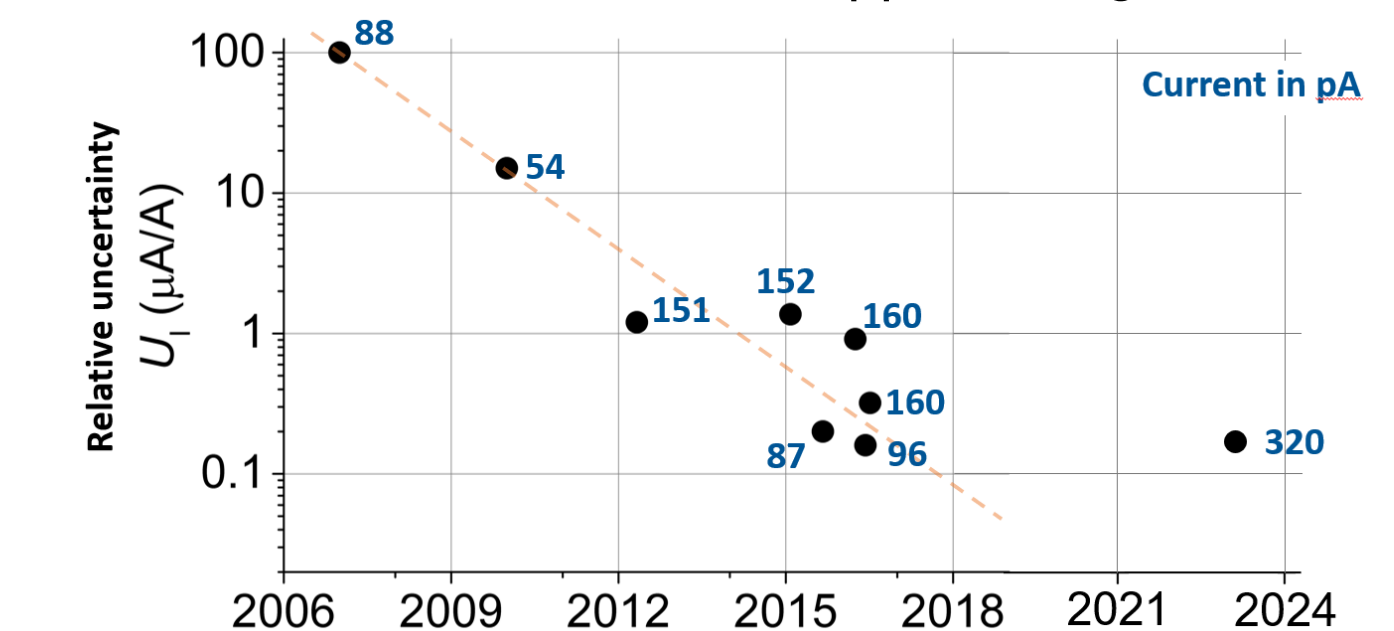
Cryogenic measurement system



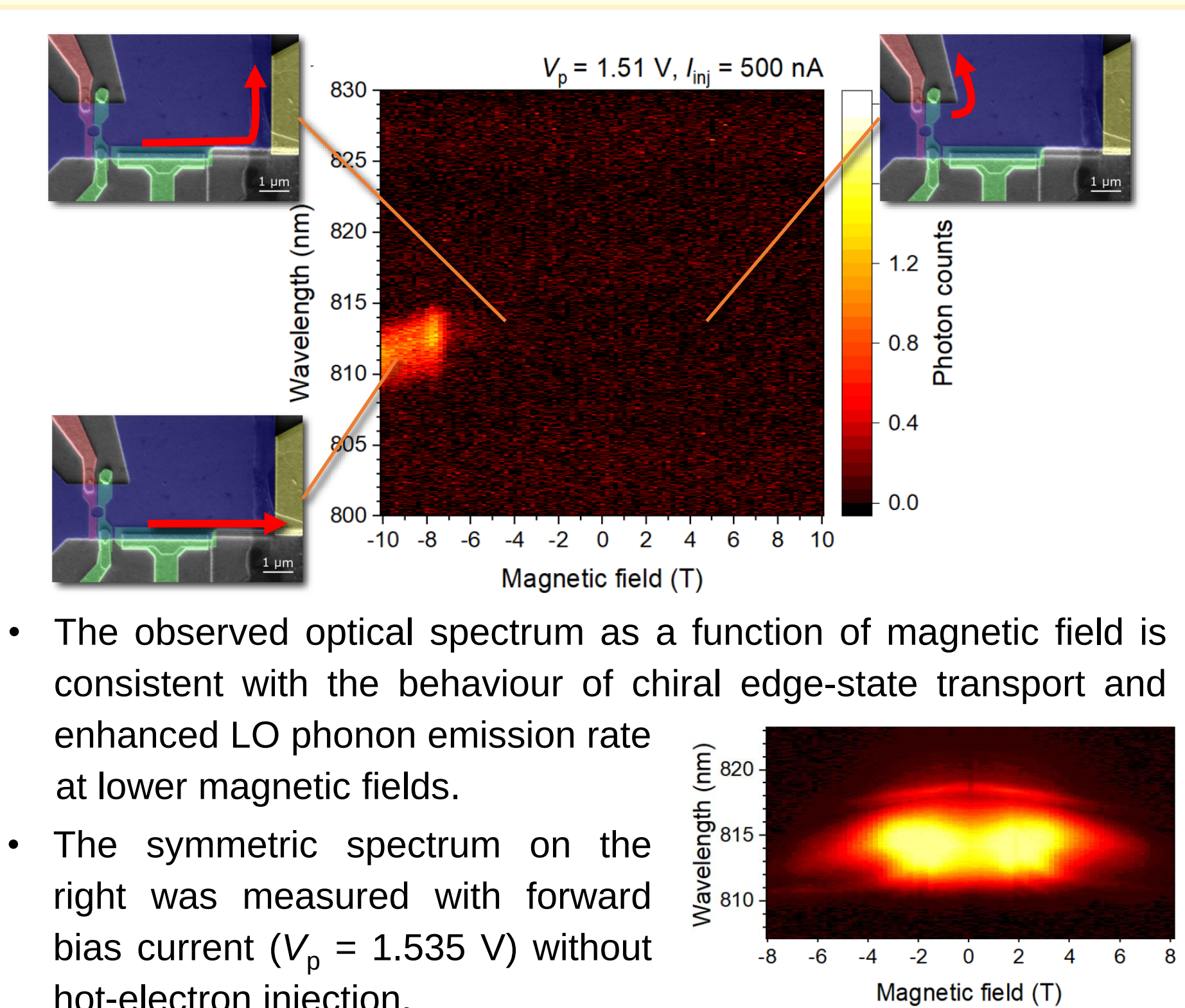
Single-electron pump



- A tunable-barrier quantum dot pump consists of a channel of two-dimensional electron gas, an entrance-barrier gate, and an exit-barrier gate.
- A radio-frequency drive on the entrance-barrier gate pumps electrons, emitting them as hot electrons.
- The number of electrons pumped per cycle can be tuned by the voltage on the exit-barrier gate.
- The timing of electron emission can be controlled with one picosecond resolution.
- In a magnetic field applied perpendicular to the plane of the two-dimensional electron gas, electrons are emitted into high-energy edge states.
- The error rate of electron transfer is approaching 10^{-7} .



Optical spectrum



- The observed optical spectrum as a function of magnetic field is consistent with the behaviour of chiral edge-state transport and enhanced LO phonon emission rate at lower magnetic fields.
- The symmetric spectrum on the right was measured with forward bias current ($V_p = 1.535$ V) without hot-electron injection.

Conclusion and perspective

- We demonstrated that photon emission can be produced by injecting hot electrons across a *pn* junction, a step towards on-demand single-photon emission by single-electron injection.
- We hope to use such devices to interconnect single-electron circuits and single-photon systems, forming a node in the Quantum Local Area Network planned at NPL.
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