Towards an all-electric, on-demand single photon source

F. Sfigakis[*,1], L. Tian[1], B. Buonacorsi[1], A. Shetty[1], S. Hosseini[1], H. Kim[1],
N. Sherlekar[1], M. C. Tam[1], F. Hohls[2], Z. Wasilewski[1], M. Reimer[1], J. Baugh[1]
[1] *University of Waterloo, Waterloo, Canada*
[2] *Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

Section I: Background

Goals & Methods

- Create a single photon source with the following ideal attributes:
  - be on-demand (deterministic, neither heralded nor stochastic);
  - be all-electric (no optical pumping with bulky lasers);
  - have high fidelities (>99%);
  - be scalable (fully integrable with semiconductor industry);
  - have high emission rates, up to 10^9 photons per second;
  - operate at 4K (or above); and
  - emit at telecom wavelengths (λ ~ 1.55 μm), for fiber networks.

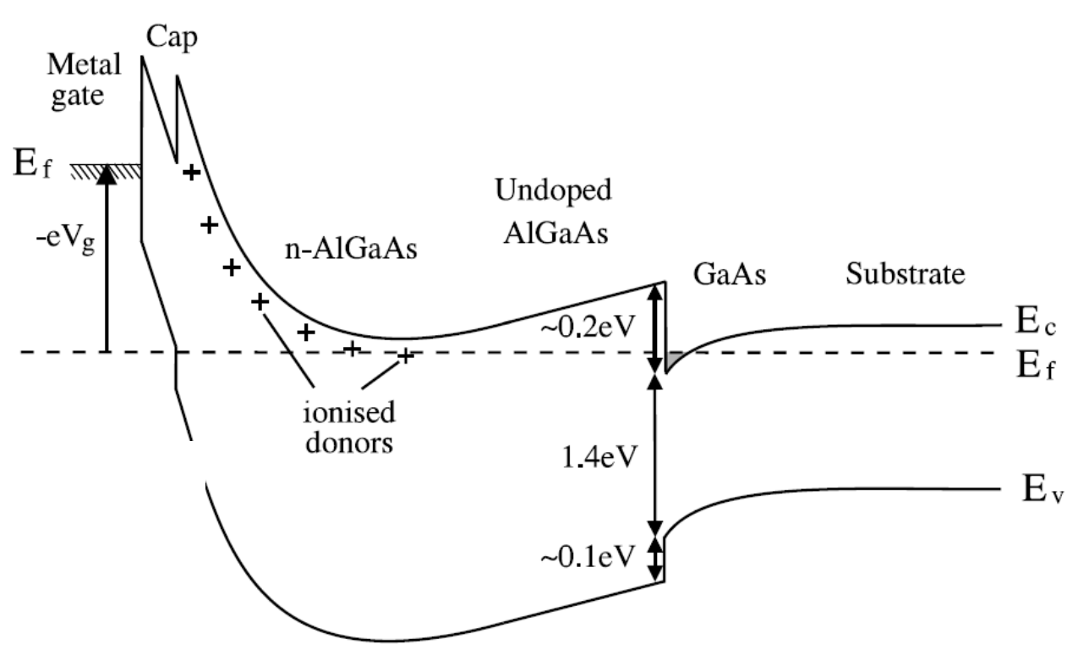
- Achieve this by placing a high-fidelity metrological single electron pump next to a lateral p-i-n junction in a 2D system, with a 2D electron gas (2DEG) on one side and a 2D hole gas (2DHG) on the other side. Single electrons are then pumped across the p-i-n gap and recombine with holes to produce single photons.

- Lateral p-i-n junctoins must be realized in dopant-free 2DEG/2DHG.

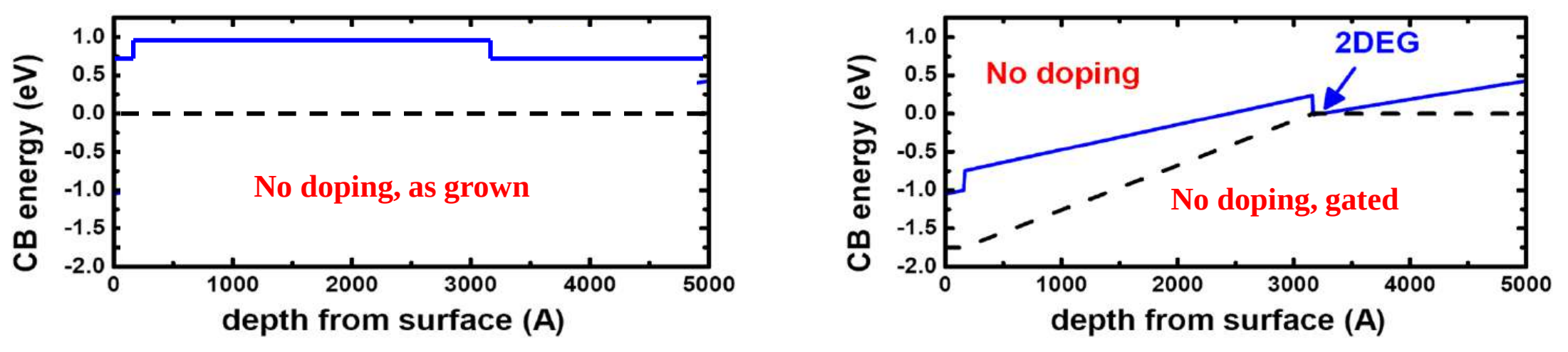
What is a dopant-free 2DEG?

- In conventionally-doped 2DEGs in AlGaAs/GaAs, both carriers and band-bending are provided by the intentional dopants (e.g., Si):

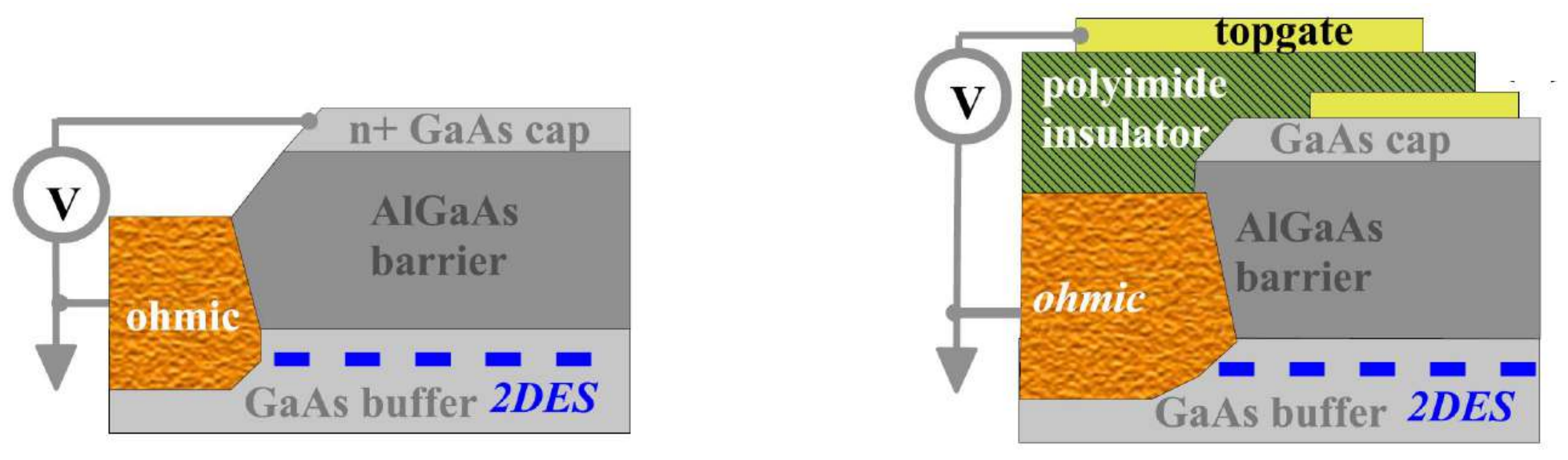
- Scattering from the intentional dopants is minimised through the use of a large undoped AlGaAs spacer layer between the 2DEG and the doped n-AlGaAs.



- By contrast, the conduction band (CB) of undoped AlGaAs/GaAs devices must be gated below the Fermi level in order to populate a 2DEG with carriers:



- An undoped 2DEG is a field-effect transistor (FET), which can come in different geometries, such as the SISFET (semiconductor-insulator-semiconductor), the HIGFET (heterostructure-insulator-gate):



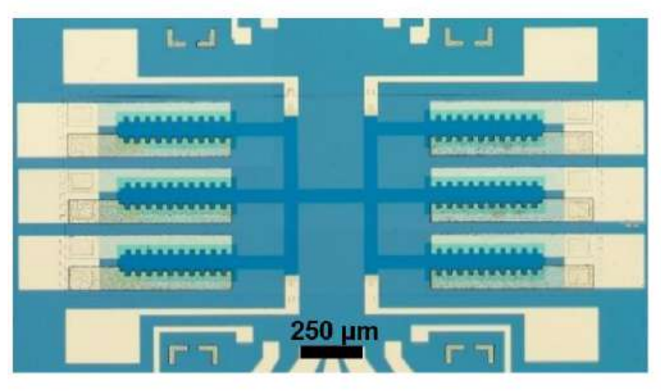
(a) a SISFET device (b) a HIGFET device

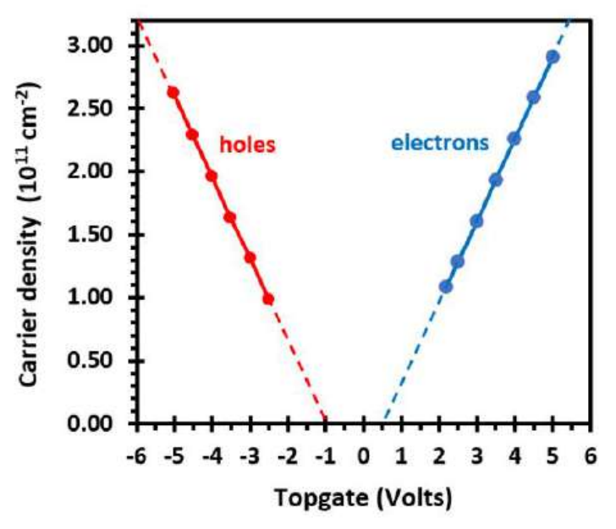
- Conventional ohmic contacts do not work on undoped 2DEGs because the topgate is screened by the metal at the surface: the 2DEG cannot form underneath, and cannot be contacted.

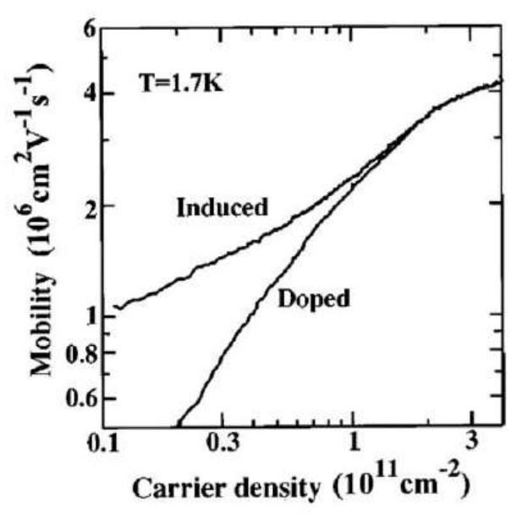
- Ohmic contacts must be recessed to promote lateral diffusion.

Advantages of dopant-free 2DEGs

- Allows ambipolar FET devices where the carrier type (electrons or holes) is solely determined by the polarity of the topgate voltage in the *same* device. This is not possible in modulation-doped samples.







- Mobilities at low carrier densities in dopant-free (induced) devices is higher than in modulation-doped devices, *i.e.* the carriers encounter fewer impurities/defects. This has a direct impact on reproducibility between devices (incl. quantum dots), and on prospects for scaling.

- All descriptions in Section I apply equally well to dopant-free 2DHGs.

- See A. Shetty et al., arXiv: 2012.14370

Acknowledgements

This research was undertaken thanks in part to funding from the Canada First Research Excellence Fund (Transformative Quantum Technologies), and under contract W7714-186539 from Defence Research and Development Canada (DRDC).

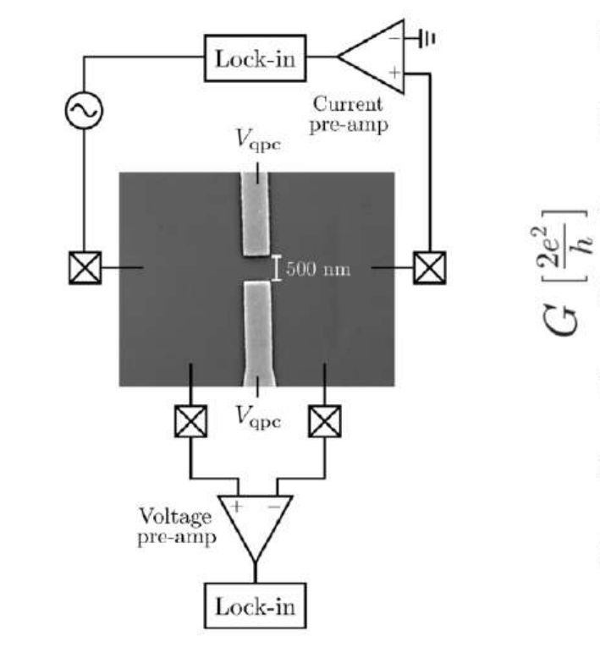
The University of Waterloo's QNFCF facility was used for this work. This infrastructure would not be possible without the significant contributions of CFREF-TQT, CFI, ISED, the Ontario Ministry of Research and Innovation, and Mike and Ophelia Lazaridis. Their support is gratefully acknowledged.

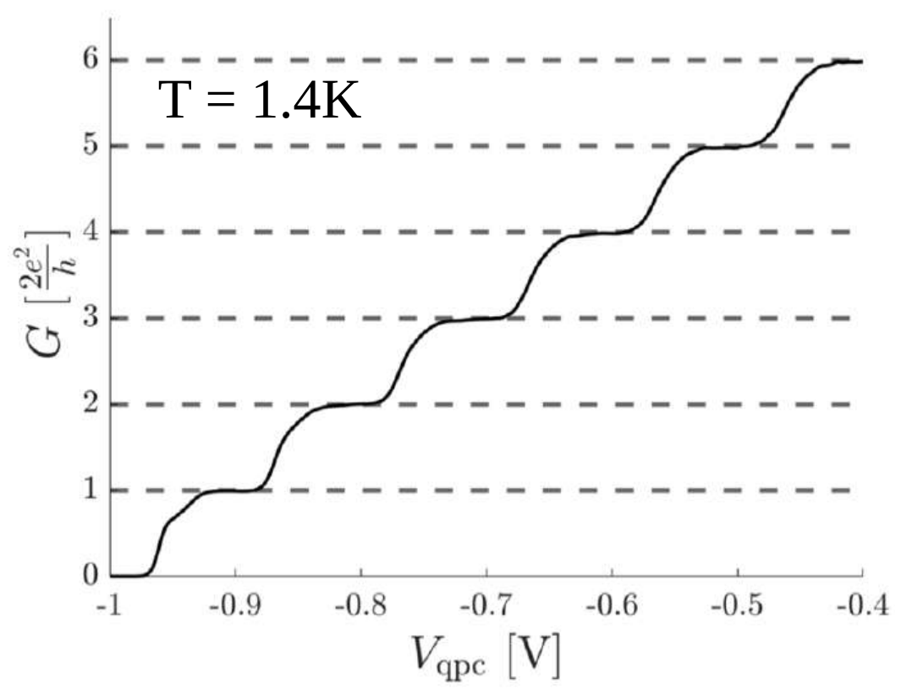
* Corresponding author: francois.sfigakis@uwaterloo.ca

Section II: Quantum Transport

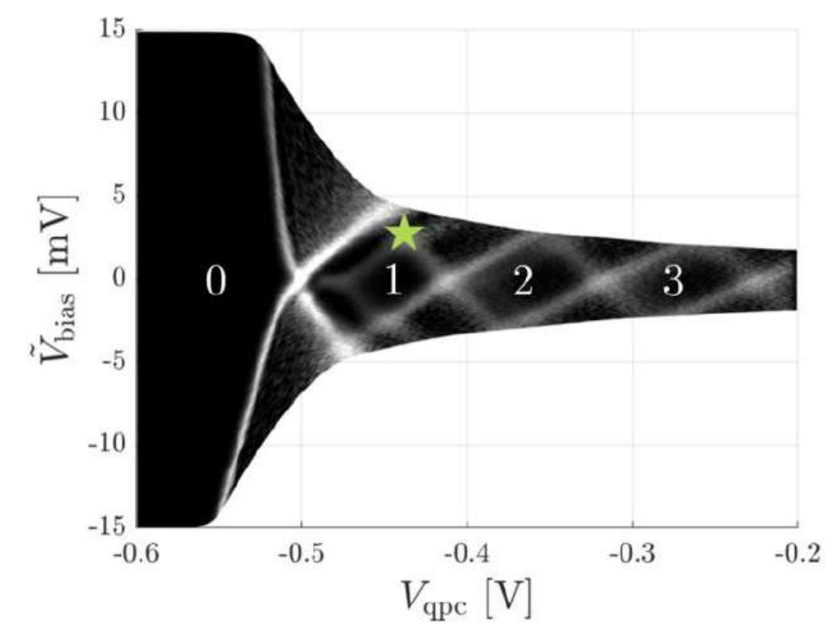
Dopant-free quantum point contacts

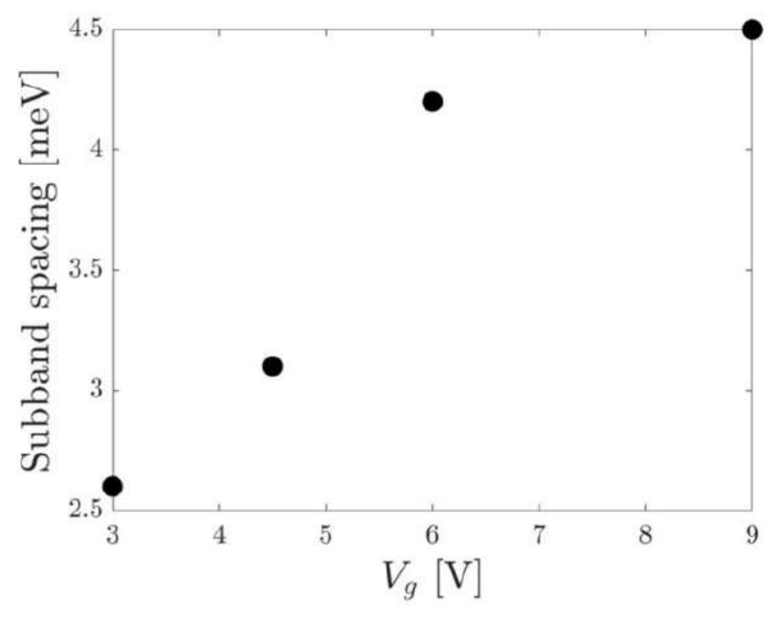
- HIGFET GaAs/AlGaAs single heterojunctions (see Section I) with the 2DEG located 75 nm or 90 nm below the surface were used for all experiments in this section. The SEM photo of the quantum point contact (QPC) was taken before the gate dielectric and topgate were deposited.





- Clean conductance steps quantized in units of $G=2e^2/h$ were observed, as well as the 0.7 structure just below the first plateau, in most devices.

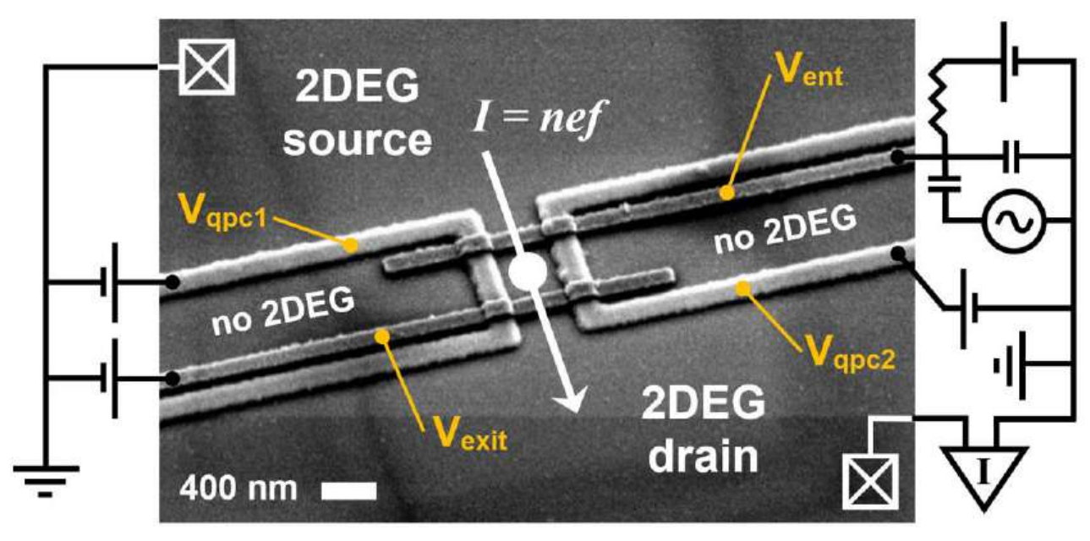


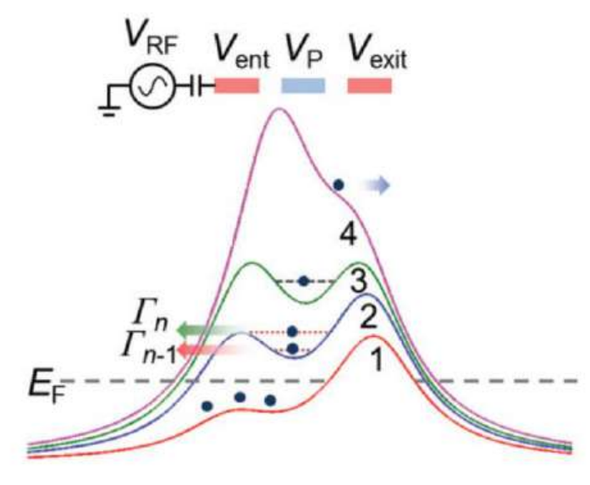


- Performing bias spectroscopy allows the measurement of the 1D energy level spacings in the QPC. Here, at a topgate voltage of +9V, the 1D subband spacing becomes 4.5 meV, one of the highest values reported for GaAs (excluding etched QPCs).

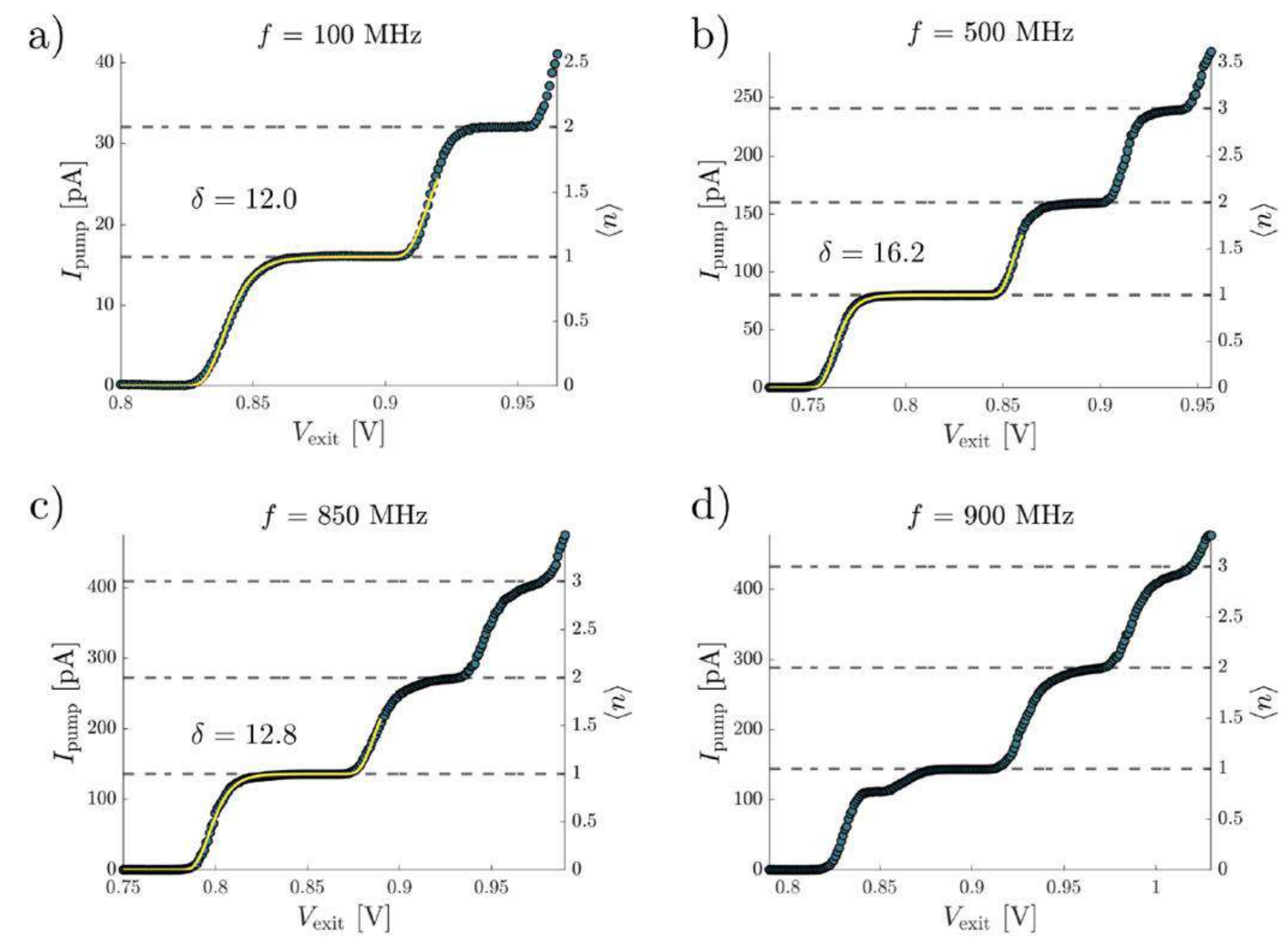
Dopant-free single electron pumps

- The SEM picture below shows a non-adiabatic single electron pump device. Note the "box design" of the V_{qpc} gates: this prevents the 2DEG from forming near the RF "entrance" gate, and thus suppresses parasitic coupling between the RF gate and the 2DEG. A thin layer of SiO_2 insulates the V_{qpc} gates from the V_{ent} and V_{exit} gates.





- For every RF cycle, an electron is "scooped" from the source reservoir and ejected into the drain reservoir. Note only one gate (V_{ent}) is operated at high frequencies. By tuning V_{ent} and V_{exit}, the number *n* of pumped electrons can be precisely controlled, producing the current $I = nef$ where the f is the frequency of a sinusoidal RF signal on V_{ent}.



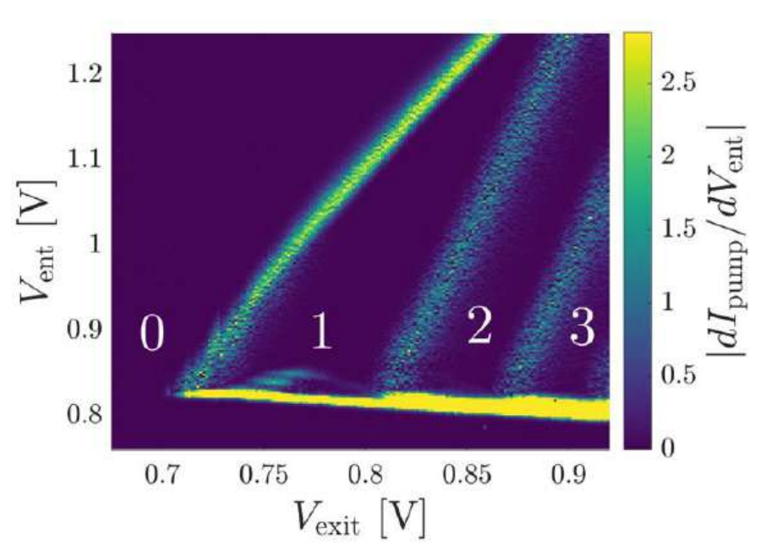
- In the above, quantized current steps are clearly visible at their expected values ($I=nef$), at frequencies up to 0.9 GHz. The experimental traces (dots) were fitted to the decay cascade model (yellow lines):

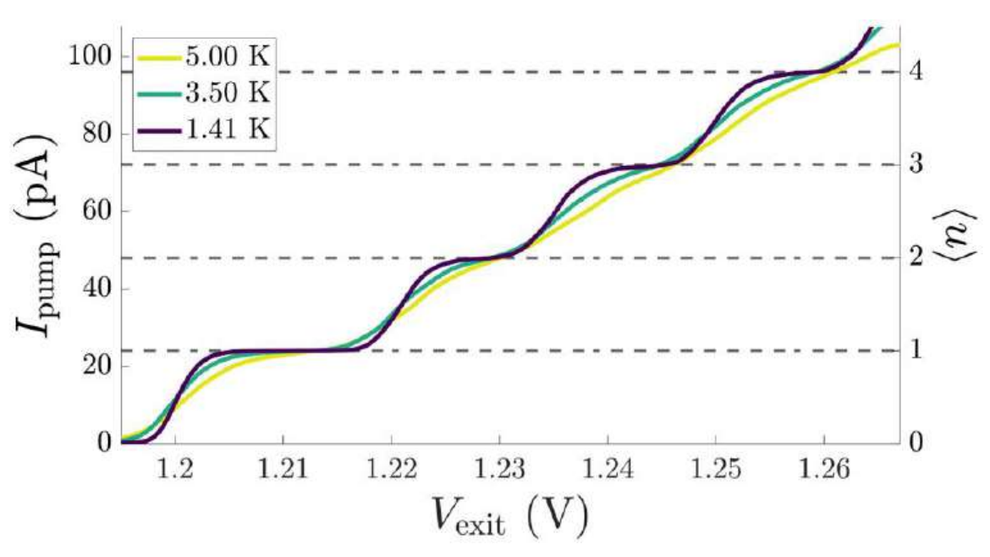
$$I/ef = \Sigma_{n=1,2} \exp(-\exp[-a(V_{exit}-V_0)+(1-n)\delta])$$

where a and δ are fitting parameters. The latter is used as a figure of merit: the higher it is, the more accurate is the pump. The estimated pumping error for the f = 500 MHz trace is just 2 ppm, comparable in performance to metrological grade single electron pumps.

- Low error levels were achieved without large magnetic fields (B>10T), without custom-shaped RF pulses waveforms, and without a dilution refrigerator, all of which are typically necessary in such pumps.

- These dopant-free pumps will be characterized at the Physikalisch-Technische Bundesanstalt, Germany's national metrology institute.





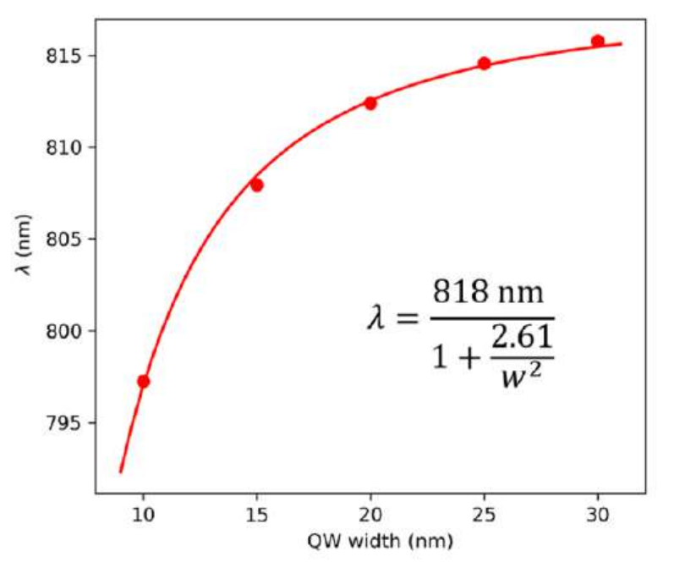
- There is very little evidence of random telegraph switching in the pump map shown above, left, which shows the derivative dI/dV_{ent} of pumped current traces for a range of V_{ent} and V_{exit} values.

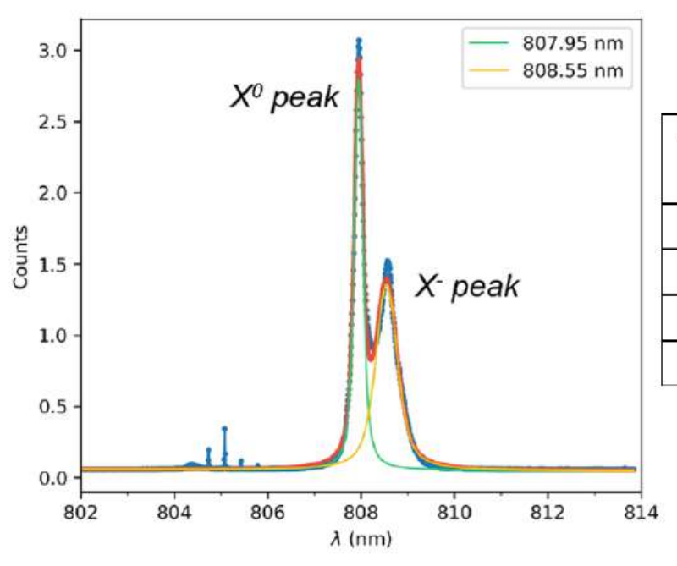
- The temperature dependence, shown above right, demonstrates the robustness of our single electron pumps, which can be used at T = 3K, the base temperature of our optical cryostat.

Section III: Optoelectronics

Photoluminescence in quantum wells

- A series of GaAs/AlGaAs quantum wells (QW) structures with widths from 10 nm to 30 nm were grown and characterized by photoluminescence (PL) with a HeNe laser. A typical spectrum is shown below.



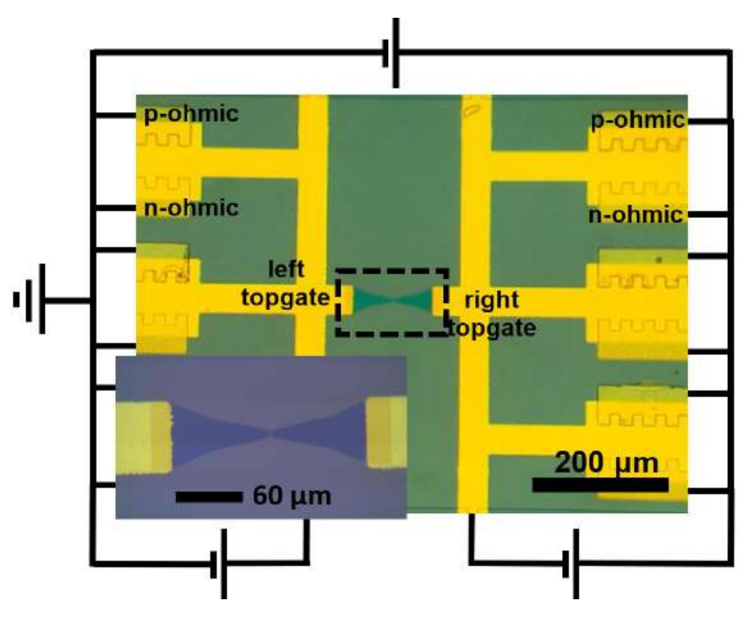


width (nm)	λ (nm)	Δλ (nm)	ΔE (meV)
10	797.4	0.37	0.73
15	808.0	0.23	0.43
20	812.4	0.21	0.39
30	815.8	0.15	0.28

- The PL emission wavelength of the neutral exciton X^0 as a function of QW width is well-behaved and can be modeled (see above, left).

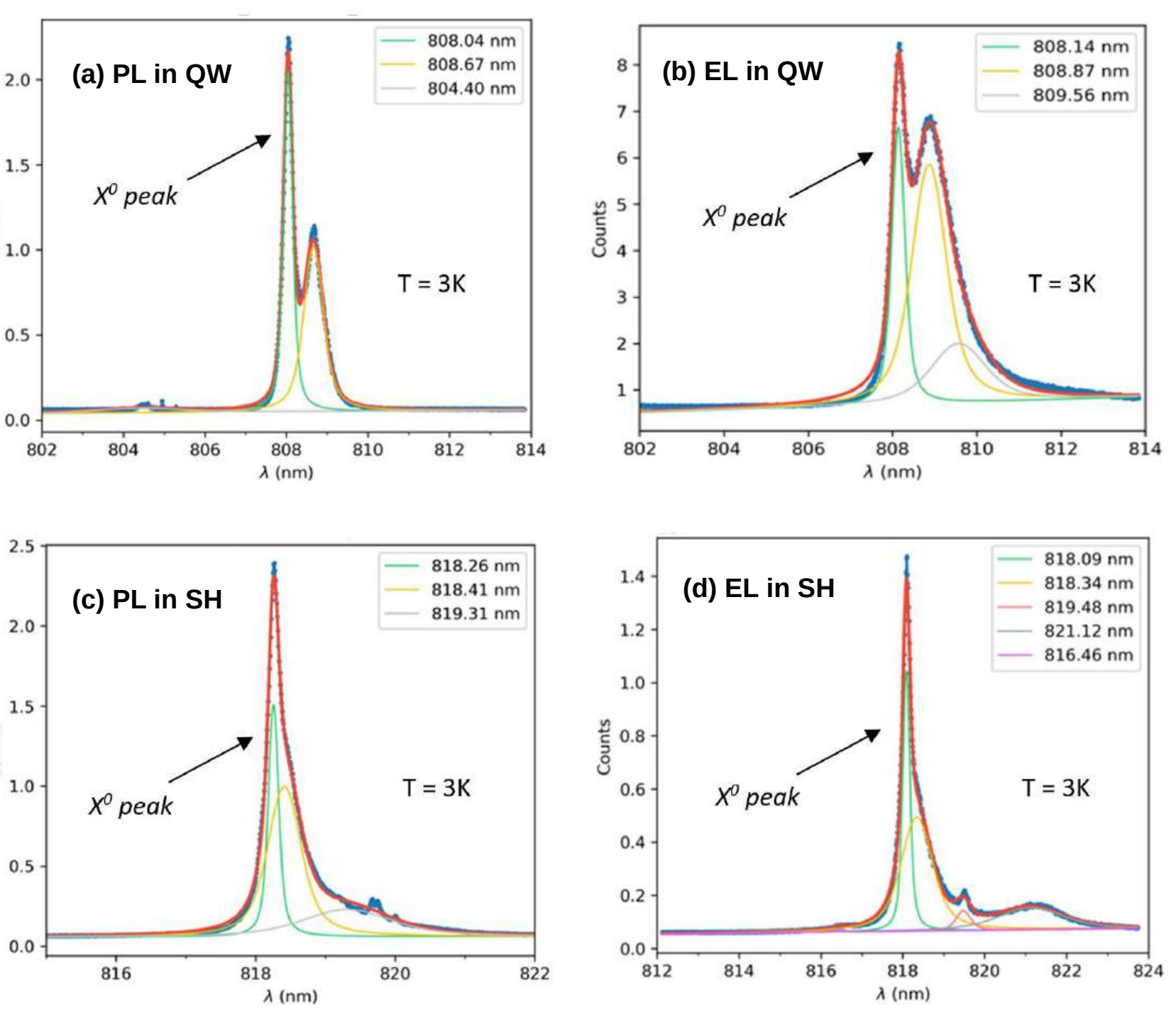
- As the QW width increases, the PL linewidth Δλ of the X^0 peak decreases (and similarly for the X^- peak, not shown), consistent with mobility increasing with QW width. The linewidth for our widest QW, 0.28 meV, is not far from the state-of-the-art (0.14 meV).

Electroluminescence from 2DEG/2DHG



- The picture opposite shows a lateral pn junction with ambipolar ohmic contacts (can be n-type or p-type), with a semi-transparent 5 nm thick Ti topgate near the pn junction gap (dashed rectangle).

- Below, we compare the PL spectra and the electroluminescence (EL) from pn junctions fabricated on dopant-free quantum quantum wells (QW) or single heterojunctions (SH). The blue dots are the experimental data, the red line is a simulated spectrum, and the green line is the fit to the X^0 peak.

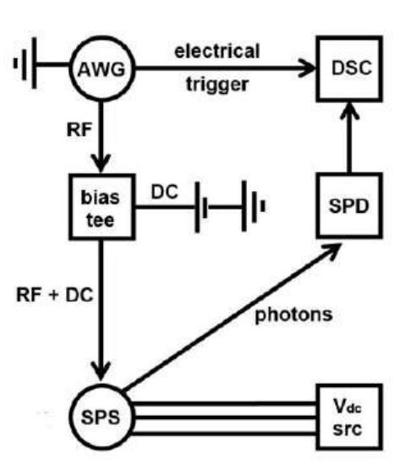


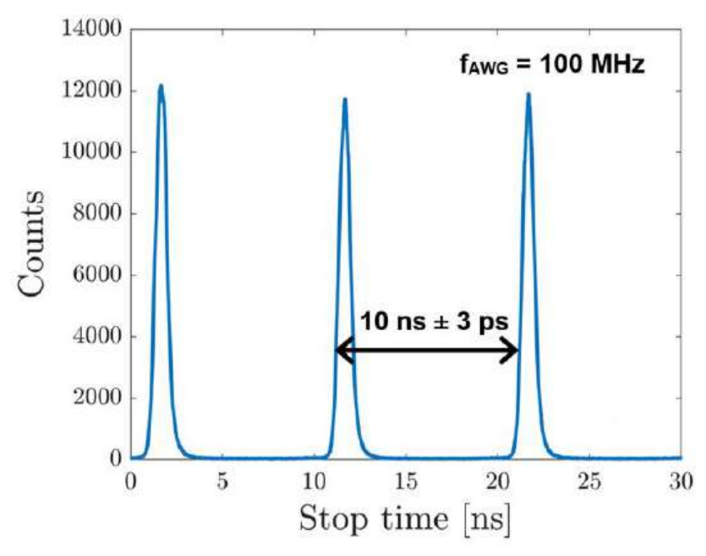
For the X^0 peak:
E_{PL} = 1.5344 eV
E_{EL} = 1.5342 eV

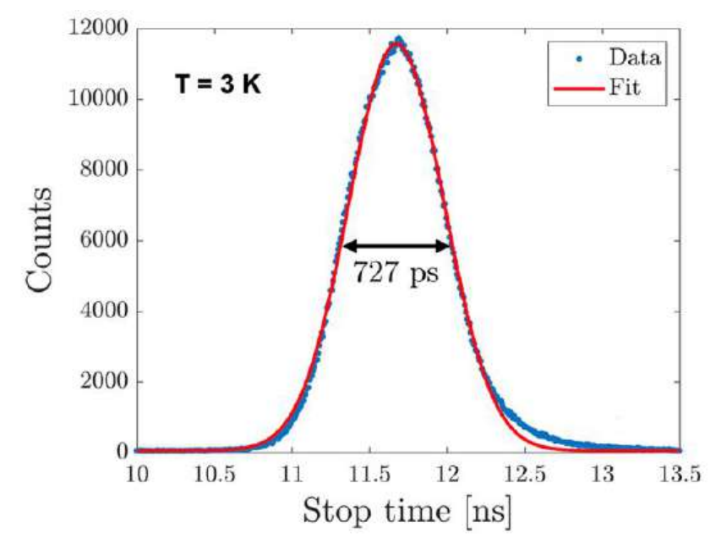
For the X^0 peak:
E_{PL} = 1.5152 eV
E_{EL} = 1.5155 eV

RF-modulated electroluminescence

- Time-resolved EL was performed on a pn junction from a single-heterojunction to measure its exciton lifetime, using the circuit below.







- Although the RF pulse was a symmetric Gaussian, the device's EL response (blue line) was not purely Gaussian: its right-hand side is elongated in time with respect to a pure Gaussian (red line).

- Fitting the convolution of a Gaussian with a decaying exponential to the right-hand side yielded a (pure) Gaussian FWHM of (558±2) ps and a neutral exciton lifetime of (281±2) ps.

- The exciton lifetime extracted from EL (281 ps) is considerably shorter than that obtained from time-resolved PL, 1250 ps. However, this could be possible, since PL was performed at energies well above the GaAs bandgap, whereas the EL was performed at the very edge of the conduction band.

Conclusions and Future Work

- First-ever non-adiabatic single electron pump in dopant-free GaAs 2DEG; possible candidate suitable for a quantum standard of current (at the nA level).

- First-ever lateral p-i-n junction in a dopant-free GaAs/AlGaAs single heterojunction, capable of operating at GHz frequencies.

- Combine the two elements above to attempt a single photon source.

- Alternatively, Leviton pumps could be used instead of non-adiabatic single electron pumps for single photon sources.