Indirect Excitons in a Potential Energy Landscape Created by a Perforated Electrode

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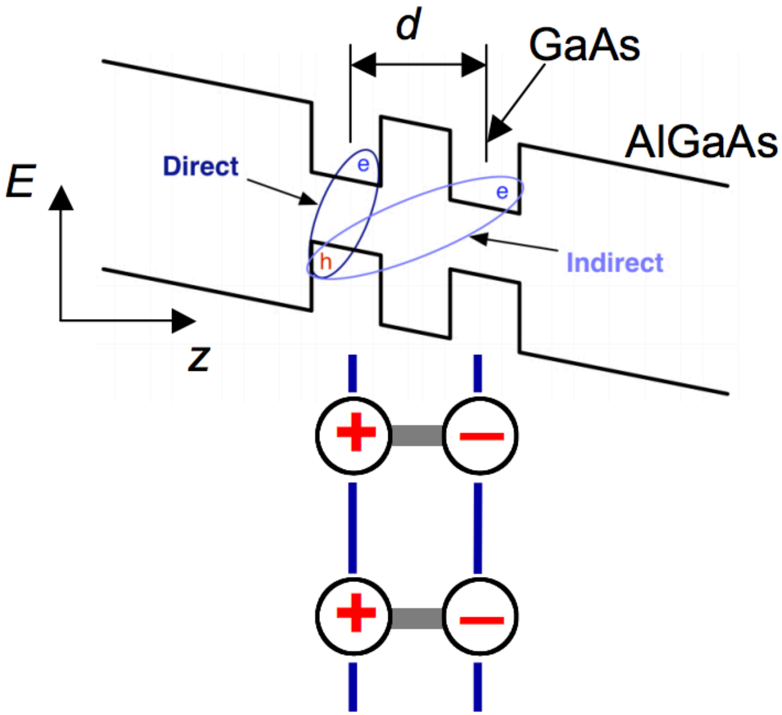
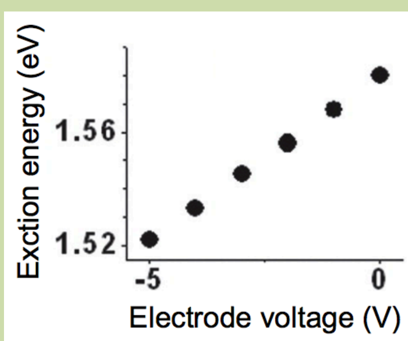
Indirect Excitons



Exciton: bound electron-hole pair

Indirect excitons:

- *e* and *h* are confined to *spatially separated* quantum wells
- Increased lifetimes and transport distances
- Oriented dipoles → disorder screening

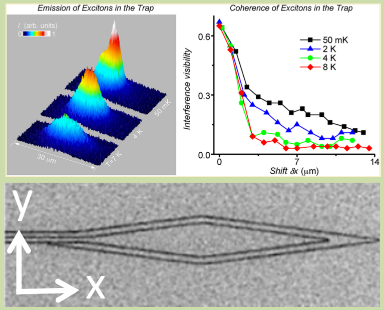


Indirect exciton energy controllable by applied voltage: $\boldsymbol{\delta E = -edF_z}$

Excitonic Devices

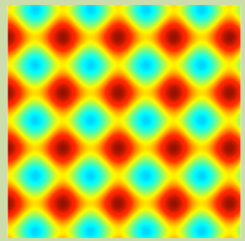
Fundamental Physics

Electrostatic traps



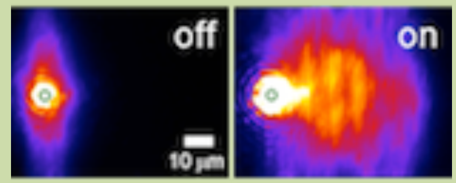
A.A. High *et al, Nano Lett.* **12**, 2605 (2012).

Exciton Lattices



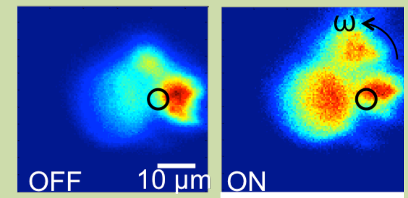
M. Remeika *et al, PRB* **92,** 115311 (2015).

Electrostatic conveyer



A.G. Winbow *et al, PRL* **106**, 196806 (2011).

Stirring potential

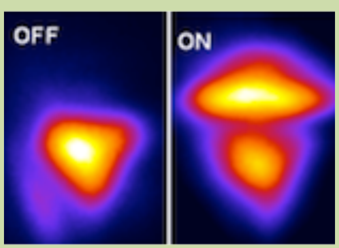


M.W. Hasling *et al, J. Appl. Phys.* **117**, 023108 (2012).

Circuit Devices

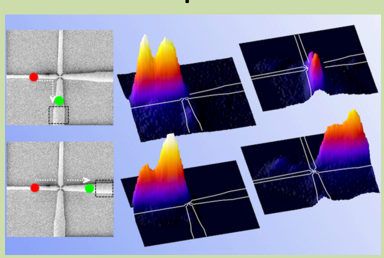
Exciton transistors:

Optoelectronic



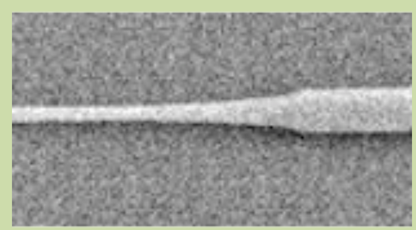
A.A. High *et al, Optics Lett.* **32**, 2466 (2007).

All-optical



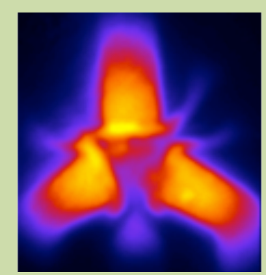
P. Andreakou *et al, APL* **104**, 091101 (2014).

Exciton ramp (diode)



J.R. Leonard *et al, APL* **100**, 231106 (2012).

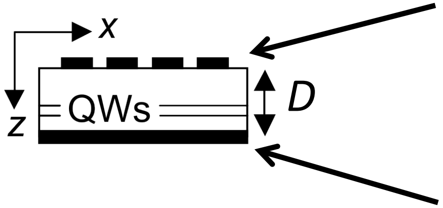
Exciton integrated circuits



A.A. High *et al, Science* **321**, 229 (2008).

more information: physics.ucsd.edu/~lvbutov

Control of Excitons by Electrode Density

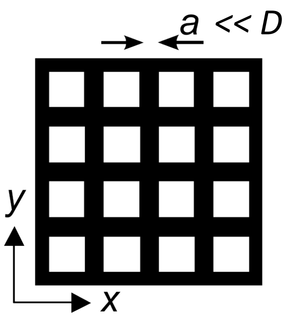


electrode pattern at *uniform* voltage

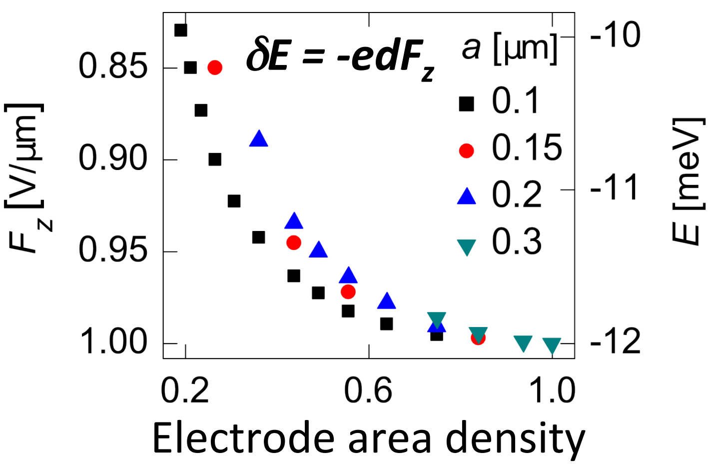
ground plane

Advantage: suppression of heating by electric currents in electrodes

Important for
- creating devices with **low energy consumption**
- studies of **ultra-cold exciton gasses**

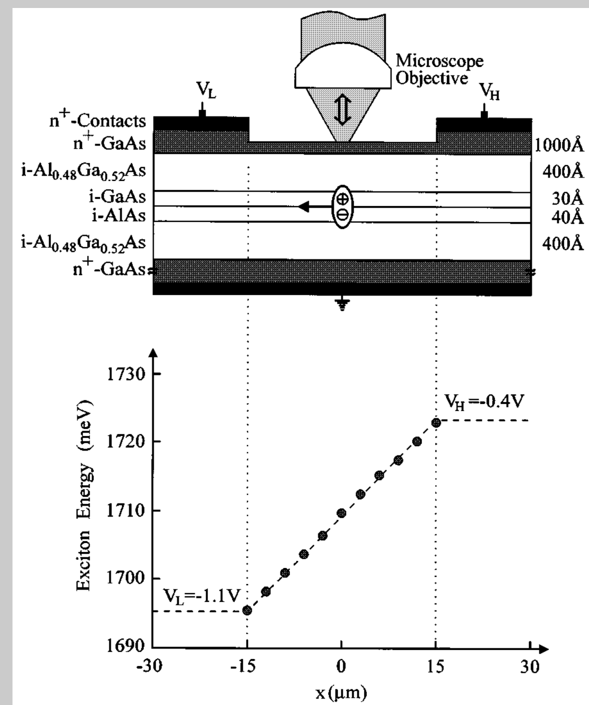


shaping the top electrode can control F_z due to fringing field



Y.Y. Kuznetsova, A.A. High, L.V. Butov, *APL* 97, 201106 (2010)

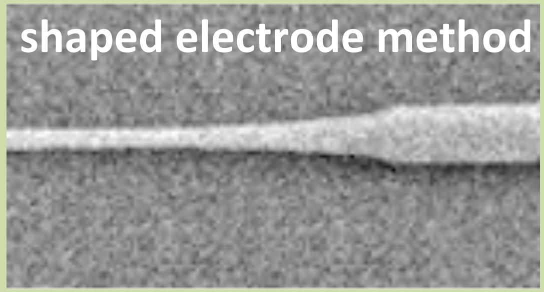
Earlier method: control of excitons by voltage gradient



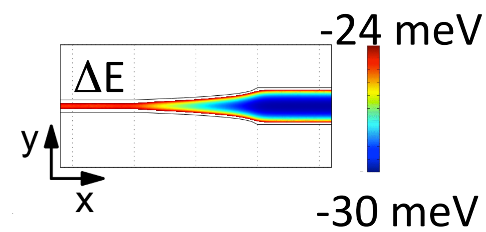
M. Hagn *et al*, *APL* **67**, 232 (1995)
A. Gartner *et al*, *APL* **89**, 052108 (2006)

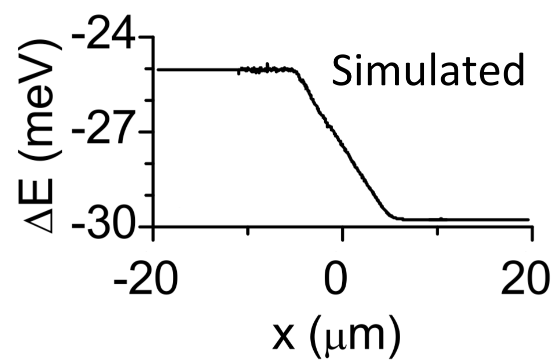
Directed Transport of Excitons

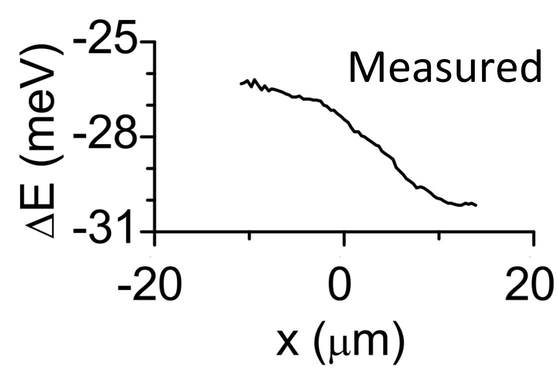
Exciton ramp



Energy profile:





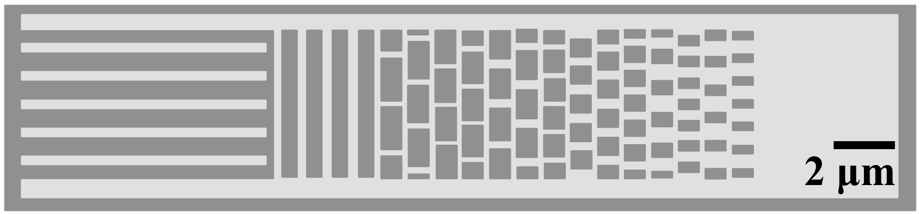


- Directs transport of excitons as a diode directs transport of electrons
- Potential energy gradient **created by shaped electrode**
- Exciton fluxes are **limited by geometry**

J.R. Leonard *et al, APL* **100**, 231106 (2012).

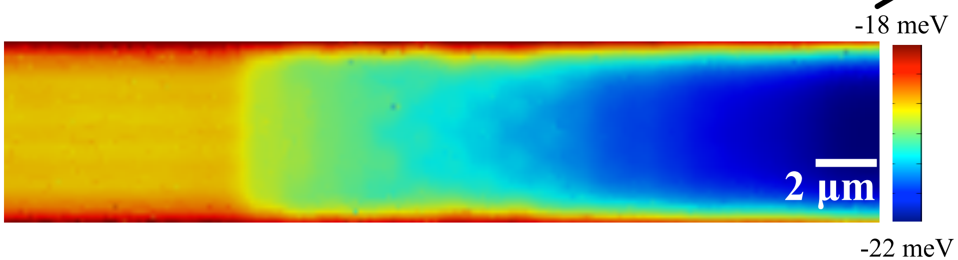
Ramp Created by Perforated Electrode Method

Electrode density modulation achieved with a **perforated electrode**

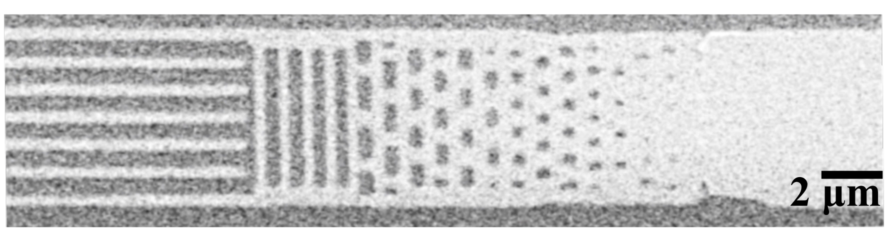


Increasing Electrode density

Decreasing Exciton energy



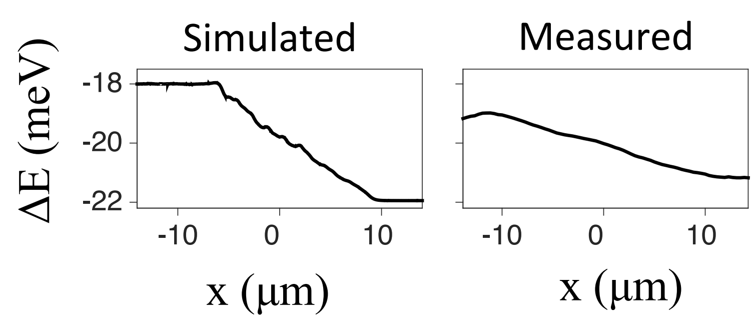
Perforated electrode SEM



Perforated electrode method

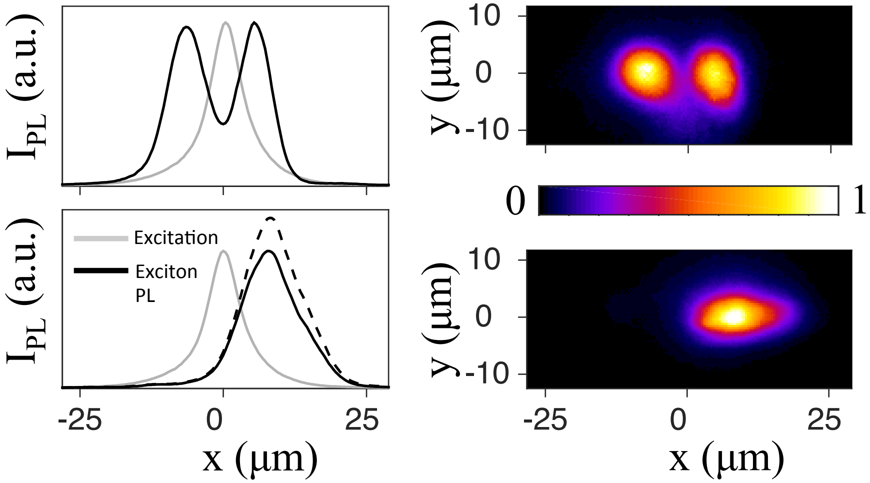
- Opportunity to create **versatile potential landscapes** for indirect excitons
- Create channels for **directing exciton fluxes** with the required geometry and energy profile
- Exciton fluxes are **not limited by geometry**

Energy profile



C.J. Dorow, Y.Y. Kuznetsova, J.R. Leonard, M.K. Chu, L.V. Butov, J. Wilkes, M. Hanson, A.C. Gossard, *APL* **108**, 073502 (2016).

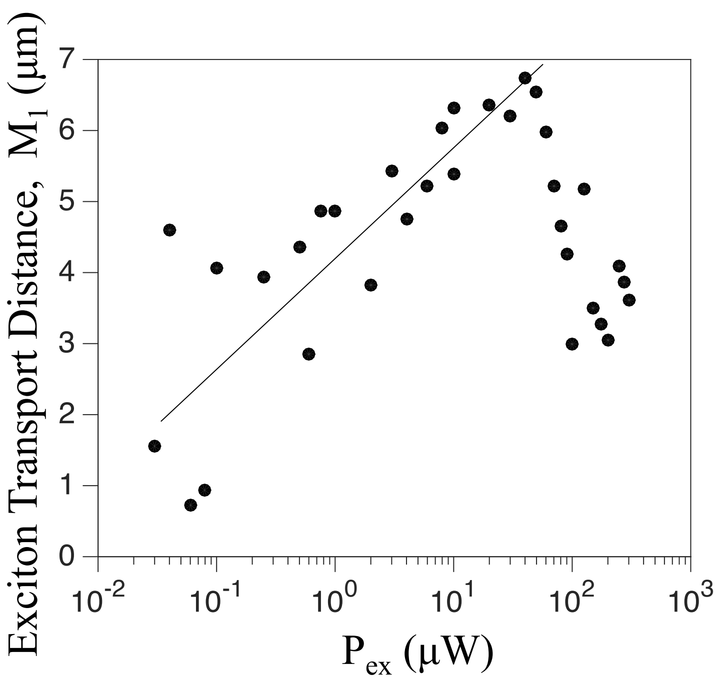
Ramp Created by Perforated Electrode Method



Flat channel,
no preferred exciton transport direction

Similar to ring due to PL enhancement outside of excitation spot
Y.Y. Kuznetsova *et al, PRB* **85**, 165452 (2012)

Ramp,
directed exciton transport



Observed exciton transport distance increase with excitation power:

higher excitation power
↓
higher exciton density
↓
better disorder screening
↓
longer transport distances

Numerical Simulations

The exciton system was modeled by solving coupled differential equations:

drift-diffusion equation

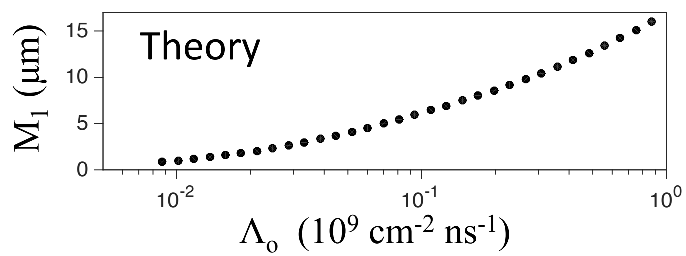
$$\nabla\left[D_x\nabla n_x + \mu_x n_x \nabla\left(u_0 n_x + U_{ramp}\right)\right] - n_x/\tau_{opt} + \Lambda = 0$$

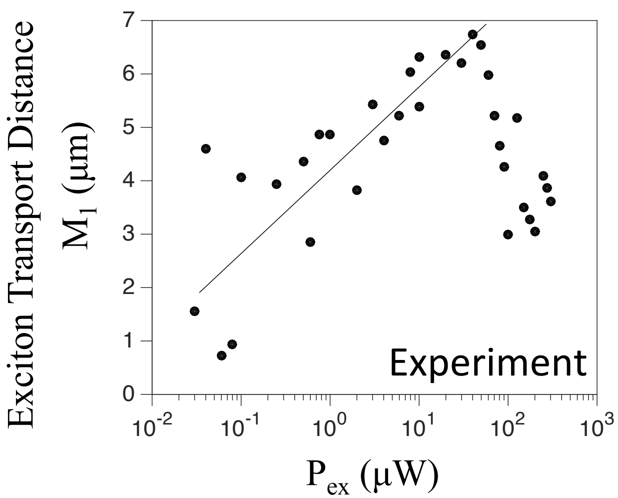
diffusion — drift — optical decay — exciton generation

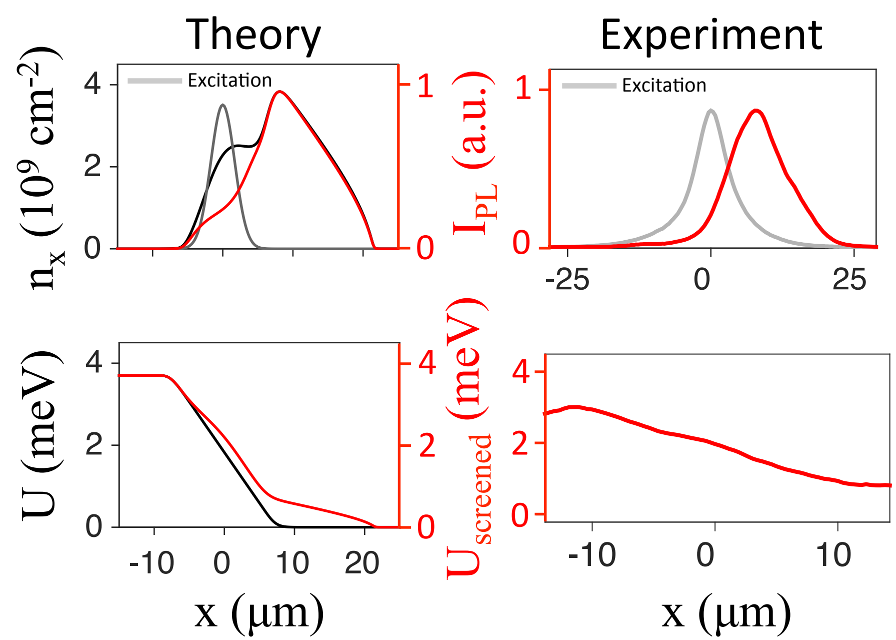
heat balance equation

$$S_{phonon}\left(T_0, T\right) = S_{pump}\left(T_0, T, \Lambda, E_{inc}\right)$$

cooling through phonons — heating due to laser excitation



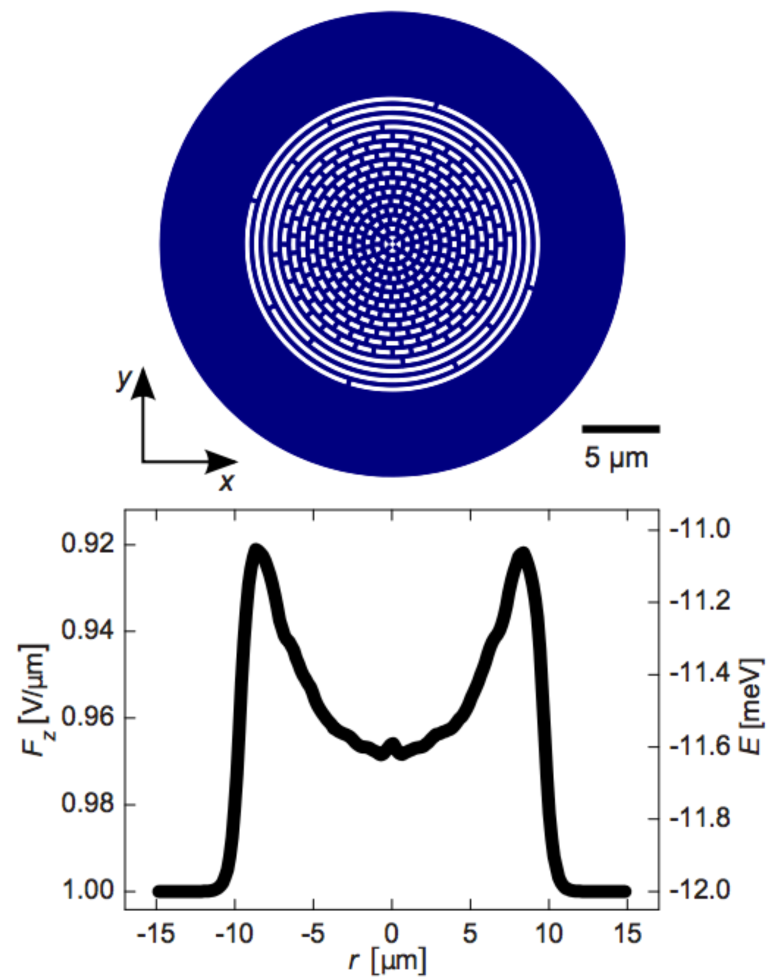




Control of Excitons: Perforated Electrode Method

Example:

Elevated trap potential created by a perforated electrode



Y.Y. Kuznetsova *et al, APL* **97**, 201106 (2010)

Ramp: **proof of principle demonstration of perforated electrode method** for controlling exciton fluxes.

Outlook:
Apply method to other types of excitonic devices

Conclusion

- We realized a linear potential energy gradient (ramp) for indirect excitons using a **perforated electrode at constant voltage**.

- The excitonic ramp realizes **directed transport of excitons** as a diode realizes directed transport of electrons.

- The ramp provides an experimental **proof of principle for the perforated electrode method of controlling exciton transport** with electrode density gradients.

- The **perforated electrode method is non-dissipative**, important for
  - creating devices with **low energy consumption**
  - studies of **ultra-cold exciton gasses**

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