Weierstrass Institute for
Applied Analysis and Stochastics

M. Kantner, M. Mittnenzweig and T. Koprucki

Modeling and simulation of electrically driven quantum light sources

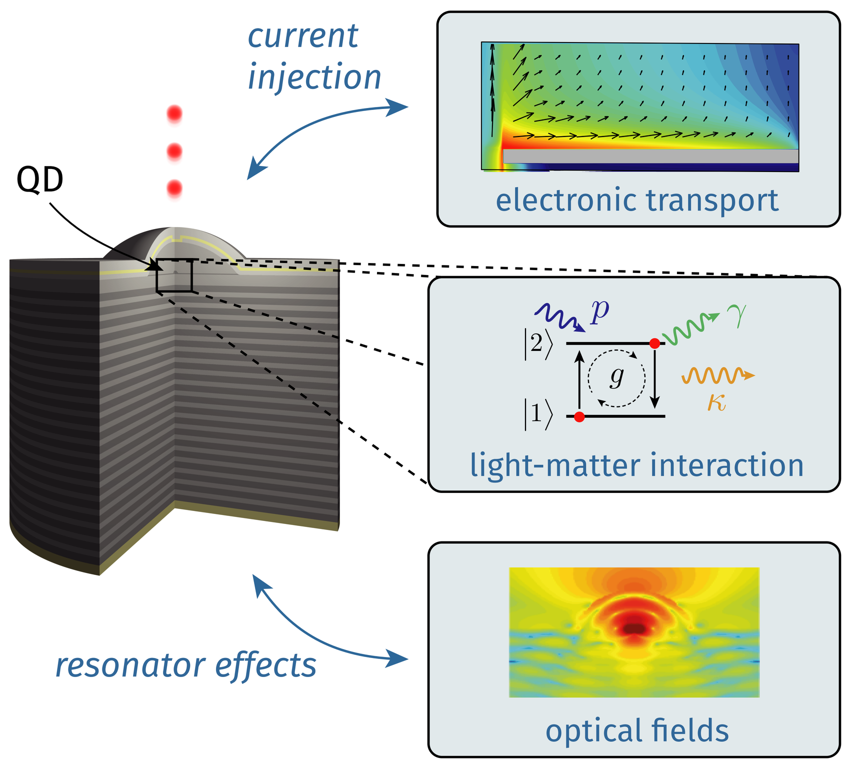
From classical device physics to open quantum systems

Semiconductor Nanophotonics SFB 787

Leibniz Association

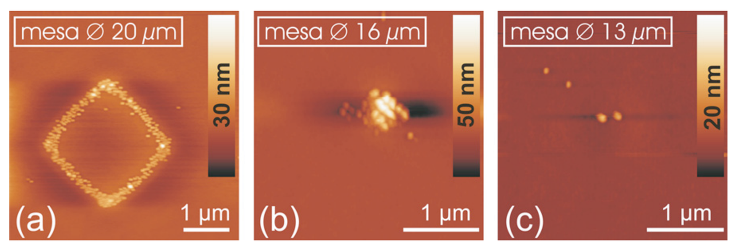
Motivation

Semiconductor quantum optics is on the leap from the lab to real world applications. In order to advance the **development of novel devices** such as quantum light sources and nanolasers based on semiconductor quantum dots embedded in dielectric micro-cavities, device engineers will need simulation tools that combine **classical device physics** with **cavity quantum electrodynamics**. We connect the fields of semi-classical semiconductor transport theory and the theory of open quantum systems to meet this requirement.

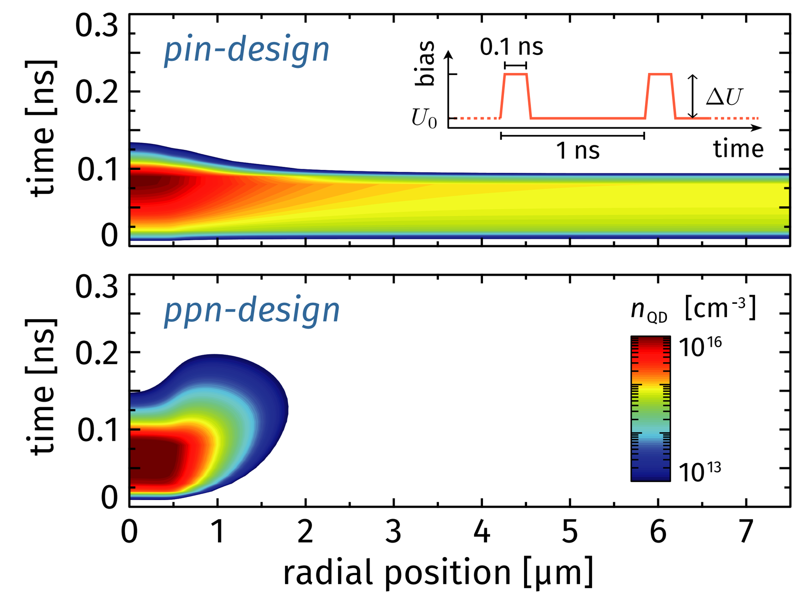


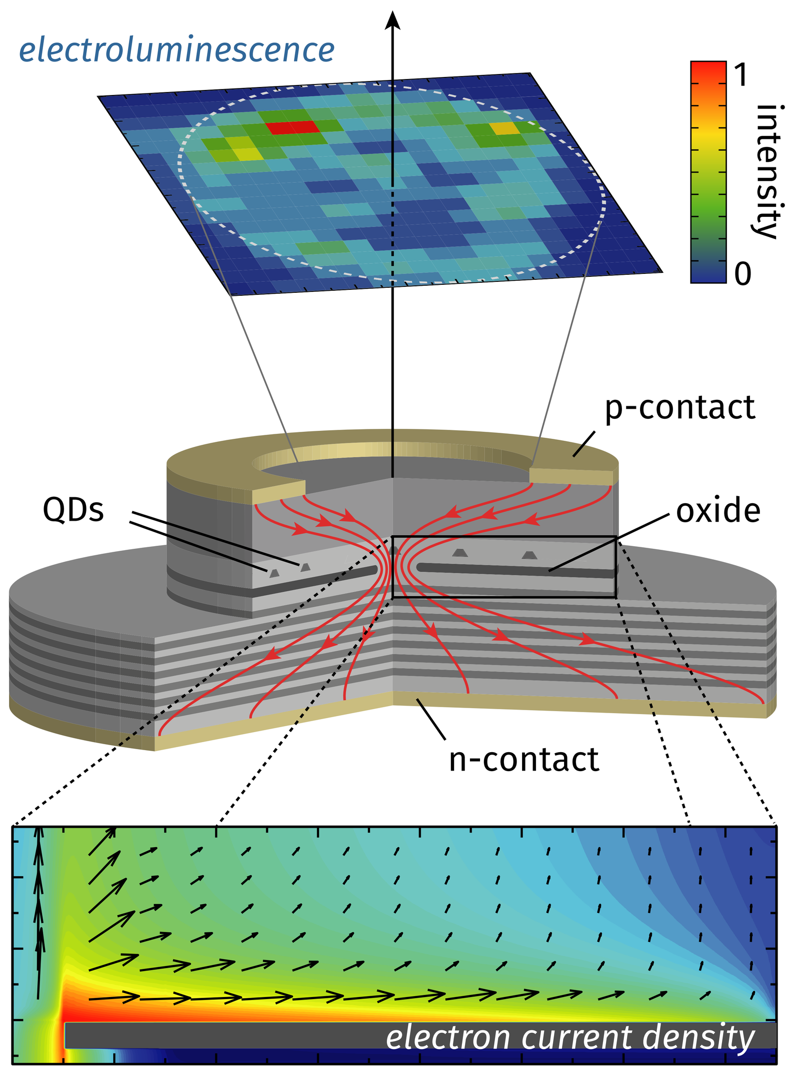
Current spreading in an oxide-confined pn-diode

- site-controlled QD nucleation above oxide aperture via buried stressor



- optical activity of parasitic QDs
- rapid **lateral curent spreading** above oxide (no bulk recombination)
- modified doping profile
  ⇨ **electrical pumping of single QDs**





Strittmatter et al., *Appl. Phys. Lett.* **100**, 093111 (2012)
Unrau et al., *Appl. Phys. Lett.* **101**, 211119 (2012)
Kantner et al., *IEEE Trans. Electron Dev.* **63**, 2036 (2016)

Hybrid quantum-classical modeling approach

Comprehensive multi-scale simulation approach for QD-based devices for quantum optics: Self-consistent coupling of **drift-diffusion system** (semi-classical charge carrier transport) with **Lindblad master equation** for dissipative QD-photon system: Spatially resolved current flow in realistic semiconductor device geometries and quantum optics out of one box!

Hybrid quantum classical model

$$-\nabla\cdot\varepsilon\nabla\phi = q\left(C+p-n+Q(\rho)\right)$$
$$\partial_t n - \frac{1}{q}\nabla\cdot\mathbf{j}_n = -R - S_n(\rho;n,p,\phi)$$
$$\partial_t p + \frac{1}{q}\nabla\cdot\mathbf{j}_p = -R - S_p(\rho;n,p,\phi)$$
$$\partial_t \rho = -\frac{i}{\hbar}[H,\rho] + \mathcal{D}(n,p,\phi)\rho$$

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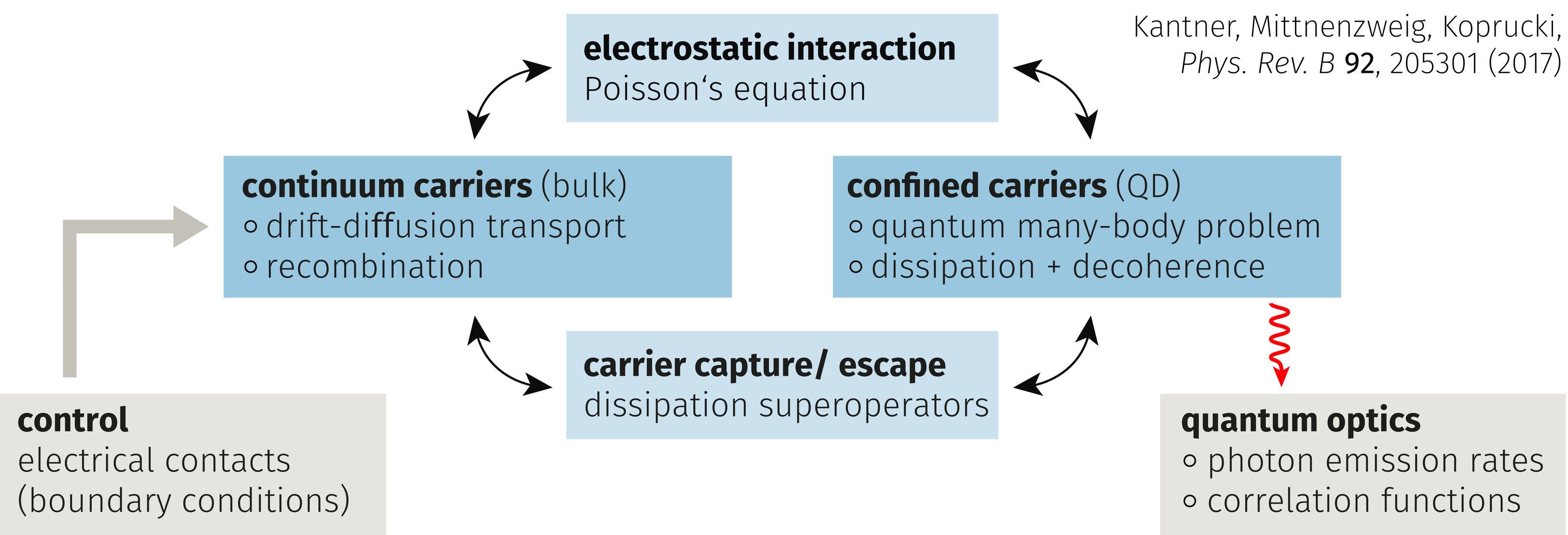
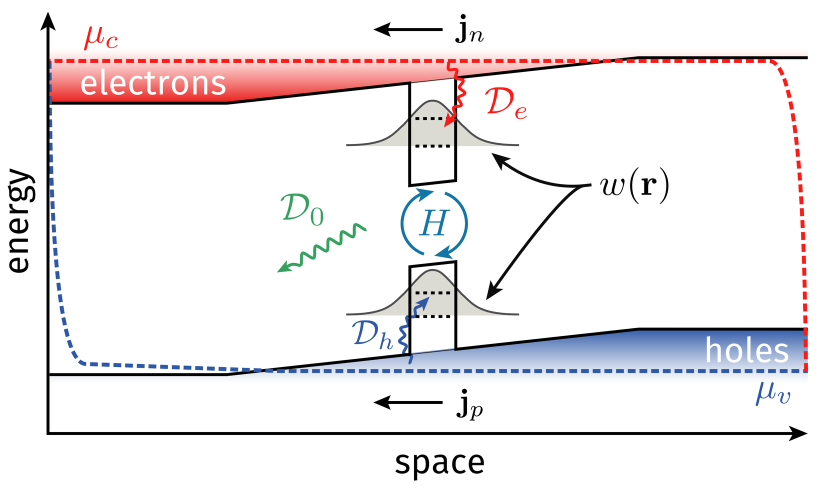




- confined charge density (QD)

$$Q(\rho) = -w(\mathbf{r})\,\mathrm{tr}(N\rho)$$

- carrier capture/ escape rates

$$S_n(\rho;n,p,\phi) = +w(\mathbf{r})\,\mathrm{tr}(N\mathcal{D}_e(n,p,\phi)\rho)$$
$$S_p(\rho;n,p,\phi) = -w(\mathbf{r})\,\mathrm{tr}(N\mathcal{D}_h(n,p,\phi)\rho)$$

⇨ local charge conservation

Consistency with (non-)equilibrium thermodynamics

Consistency with fundamental laws of (non-)equilibrium thermodynamics is considered as a guiding principle for the formulation of the quantum-classical system. By construction, the system satisfies the **conservation of charge** and thermodynamic principles such as **microscopic reversibility** in the thermodynamic equilibrium and the **second law of thermodynamics**.

- minimize (hybrid) **grand potential** in thermodynamic equilibrium

$$\Phi = \mathcal{F}(n,p,\rho) - \mu_{\mathrm{eq}}\int_\Omega \mathrm{d}^3r\,\left(n-p-Q(\rho)\right)$$

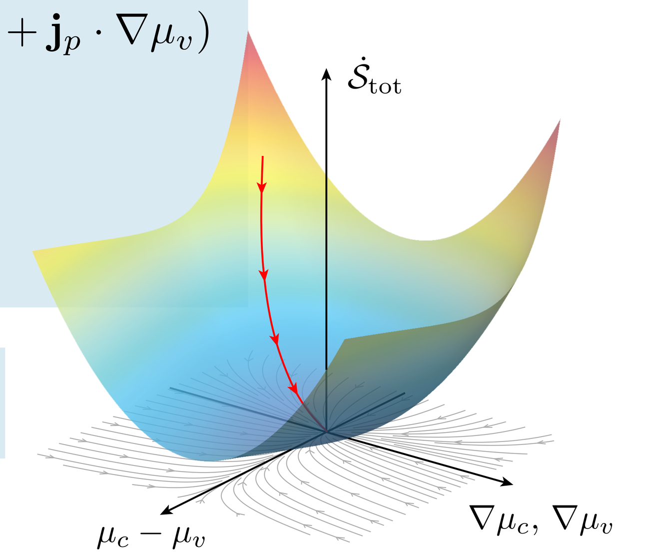
- (quantum) detailed balance relation

$$\mathcal{D}(n_{\mathrm{eq}},p_{\mathrm{eq}},\phi_{\mathrm{eq}})\rho_{\mathrm{eq}} = 0$$

entropy production rate

$$\begin{aligned}\dot{S}_{\mathrm{tot}} = {}& \frac{1}{T}\int_\Omega \mathrm{d}^3r\,(\mu_c-\mu_v)\,R + \frac{1}{qT}\int_\Omega \mathrm{d}^3r\,(\mathbf{j}_n\cdot\nabla\mu_c + \mathbf{j}_p\cdot\nabla\mu_v)\\ &+ k_B\,\mathrm{tr}\left([\log\rho - \beta H]\,\mathcal{D}_0\rho\right)\\ &+ k_B\,\mathrm{tr}\left([\log\rho - \log\rho_e^*(n,p,\phi)]\,\mathcal{D}_e(n,p,\phi)\rho\right)\\ &+ k_B\,\mathrm{tr}\left([\log\rho - \log\rho_h^*(n,p,\phi)]\,\mathcal{D}_h(n,p,\phi)\rho\right)\end{aligned}$$

- gradient structure $\partial_t z = \left(\mathbb{J}(z) - \mathbb{K}(z)\right)\mathrm{D}\mathcal{F}(z)$

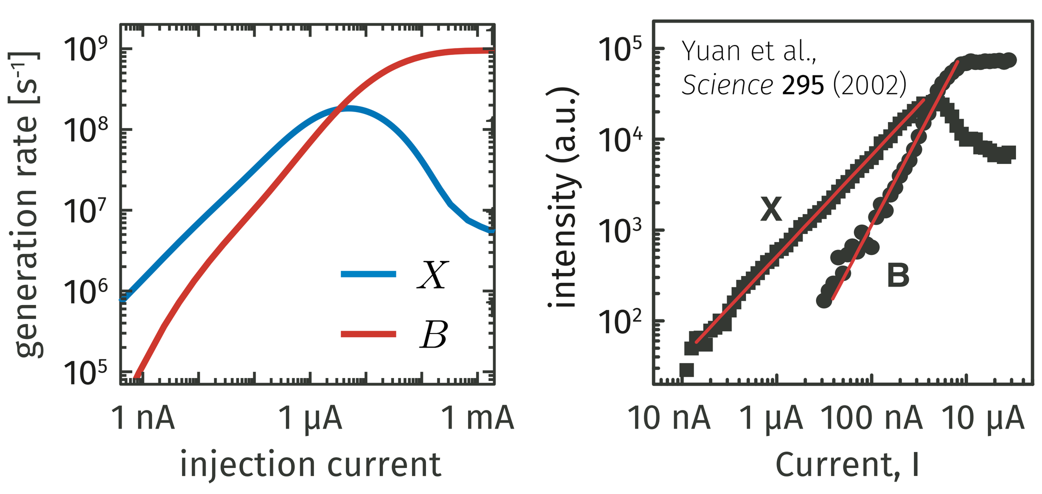


Kantner, Mittnenzweig, Koprucki, *Phys. Rev. B* **92**, 205301 (2017)
Kantner, Mielke, Mittnenzweig, Rotundo (*submitted* 2018)

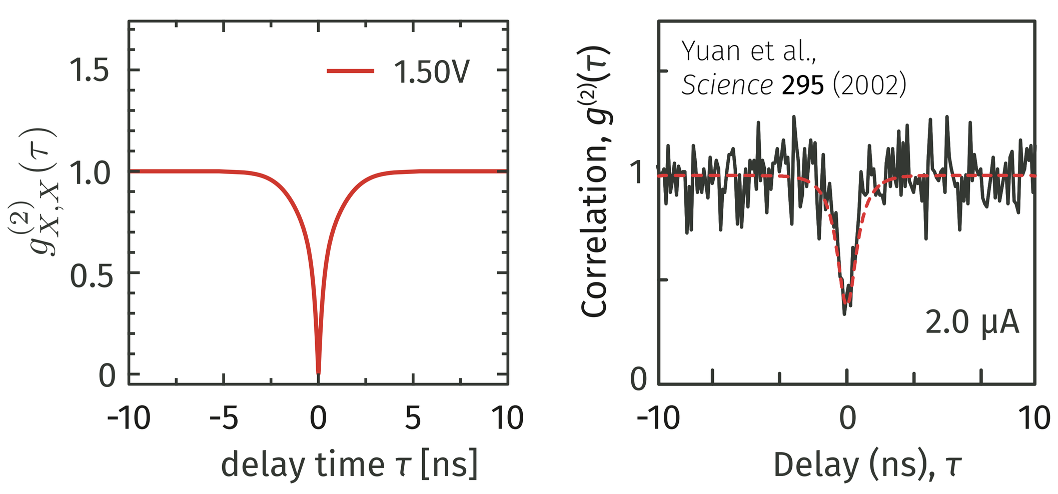
Simulation results

Stationary operation

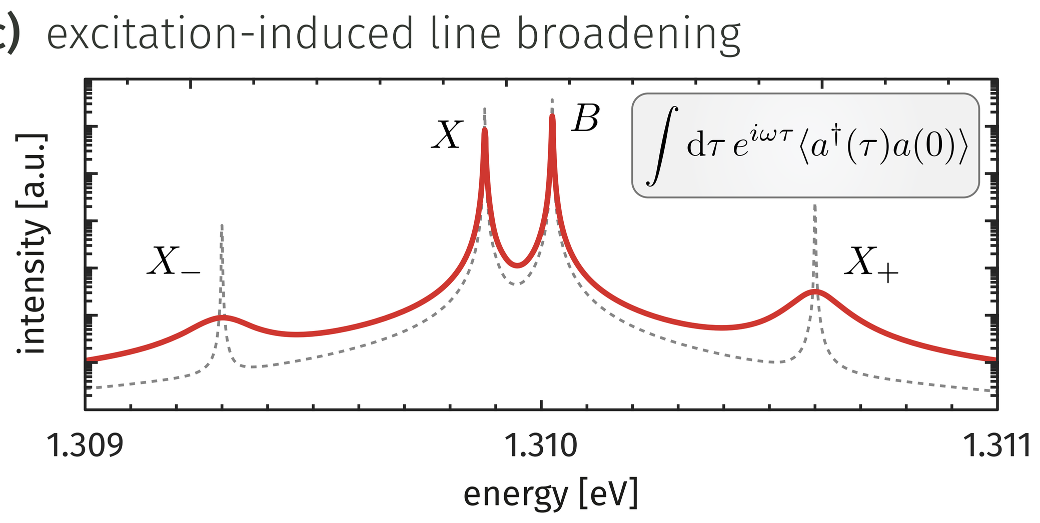
(a) single-photon generation rate



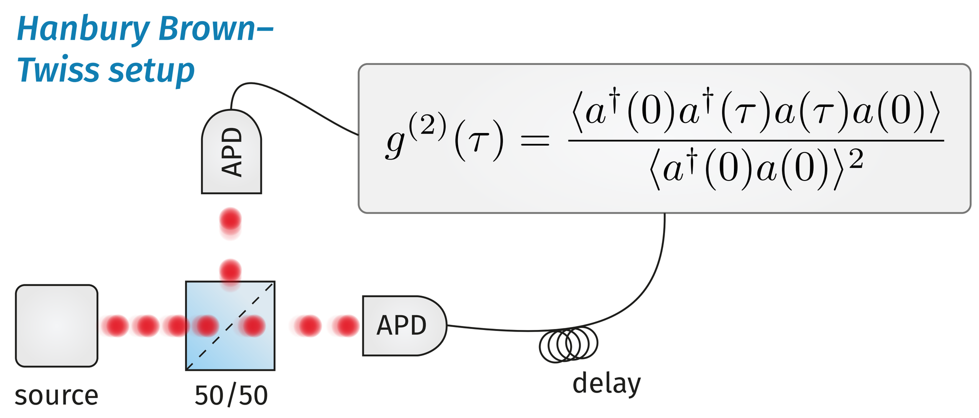
(b) second order intensity correlation function



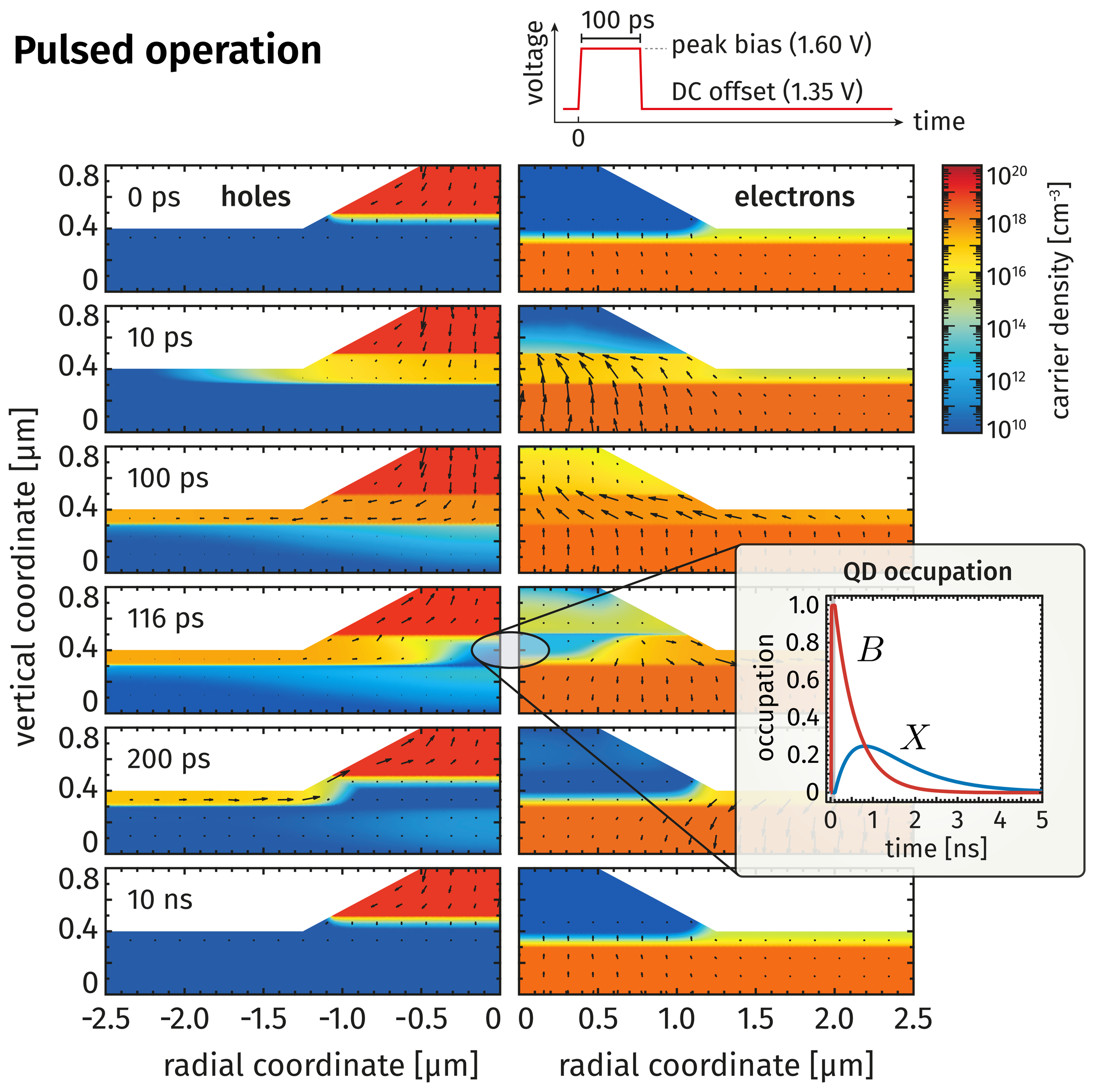
(c) excitation-induced line broadening



Hanbury Brown–Twiss setup



Pulsed operation



contact: Markus Kantner • Weierstrass Institute for Applied Analysis and Stochastics • Mohrenstr. 39, 10117 Berlin, Germany • phone: +49 (30) 20372-504 • kantner@wias-berlin.de