Electrical and Optical Gating of Thin Films of PbS Nanoparticles coupled with a Polyphenyleneethynylene Derivative

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Faculty of Science
Institute of Physical and Theoretical Chemistry
Telephone: +49 (0)7071 29 76223
Email: kai-matthias.wurst@uni-tuebingen.de

Kai M. Wurst[1], Markus Bender[2], Jannika Lauth[3], Laurens D. A. Siebbeles[3], Uwe H. F. Bunz[2], Kai Braun[1] and Marcus Scheele[1]

[1] IPTC, University of Tübingen, Auf der Morgenstelle 18, 72076 Tübingen, Germany
[2] Organisch-Chemisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 270, Heidelberg, Germany
[3] Chem. Eng. Dep., Delft University of Technology, Van der Maasweg 9, 2619 HZ Delft, The Netherlands

DFG Deutsche Forschungsgemeinschaft

BADEN-WÜRTTEMBERG STIFTUNG Wir stiften Zukunft

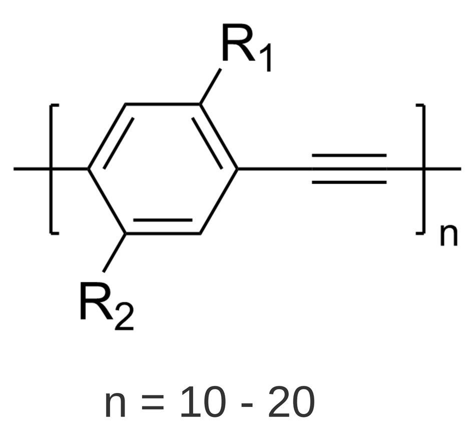
Outline

Coupled organic-inorganic nanostructures (COINs) are systems consisting of nanoparticles (NP) linked with organic semiconductors (OSC) to establish highly ordered assemblies[1]. Resonant energy level alignment in a combined system of semiconducting NP and OSC leads to a material which shows the ability of charge carrier transport paired with a characteristic field effect response. Further increase of the measured currents can be achieved by resonant optical excitation with laser light whereby the amount of generated free charge carriers depends on both the adjustable optical output power and wavelength of the used laser as well as the absorption characteristics of the investigated COINs. These material specific properties might pave the way for application as field effect transistors (FET) and light effect transistors (LET). In this work, thin films of lead sulfide NP functionalized with a polyphenyleneethynylene derivative[2] as OSC were fabricated and characterized for their behavior towards electrical and optical gating.

The Investigated System and Substrates

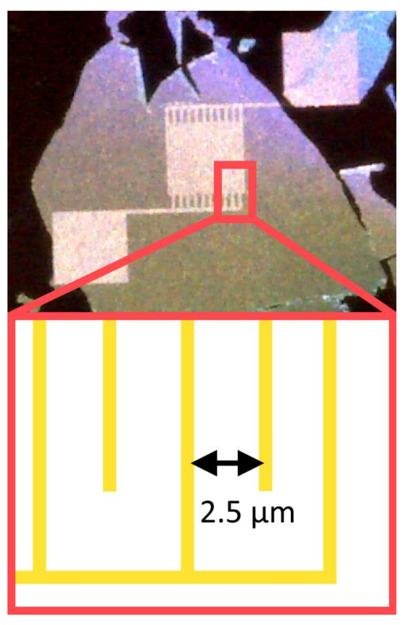
Thin films of PbS nanoparticles crosslinked with a polyphenyleneethynylene derivative were deposited on two different substrates depending on the used measurement technique: Commercial FET wafer (Fraunhofer-Institute for photonic microsystems) and self-made glass substrates with evaporated gold contacts (fabricated via photolithography, channels are cut by a focused ion beam).

OSC

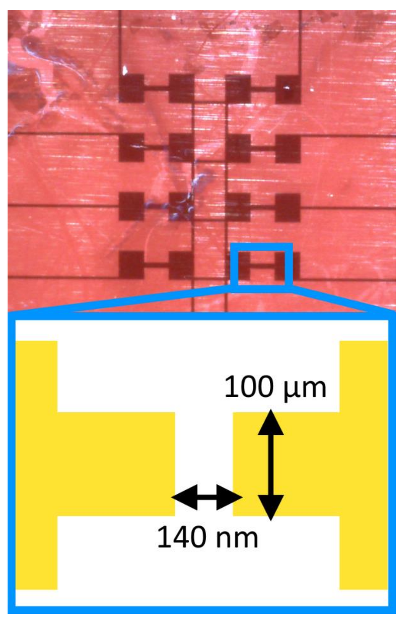


Courtesy of Markus Bender and Uwe H. F. Bunz, Heidelberg University

FET Substrate

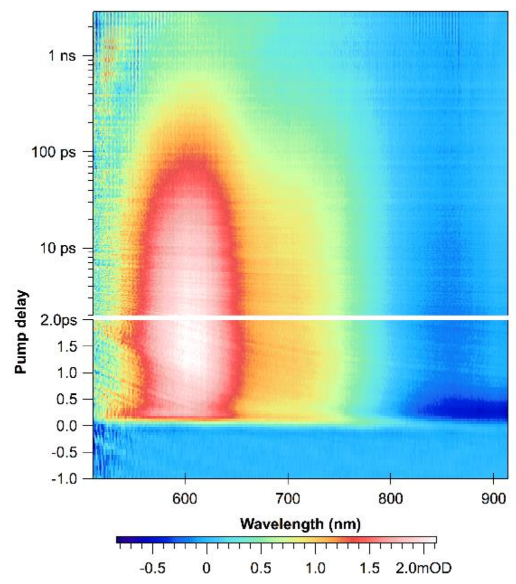


Self-made Substrate



Transient Absorption Measurements

TA measurements on the COINs (7 nm PbS NP) show a strong induced absorption at about 610 nm. The idea is to excite the material with laser light with this wavelength to generate free charge carriers resulting in a higher photocurrent than compared to illumination with light below or above 610 nm having the same optical power.

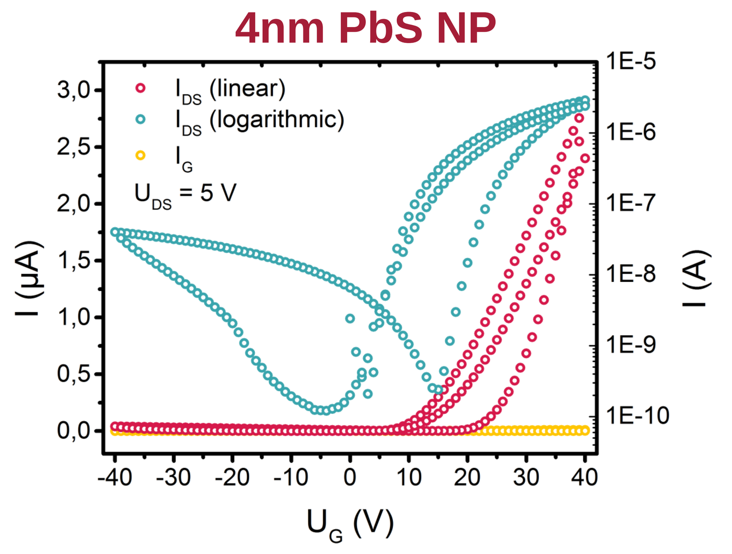


Courtesy of Jannika Lauth and Laurens D. A. Siebbeles, Delft University

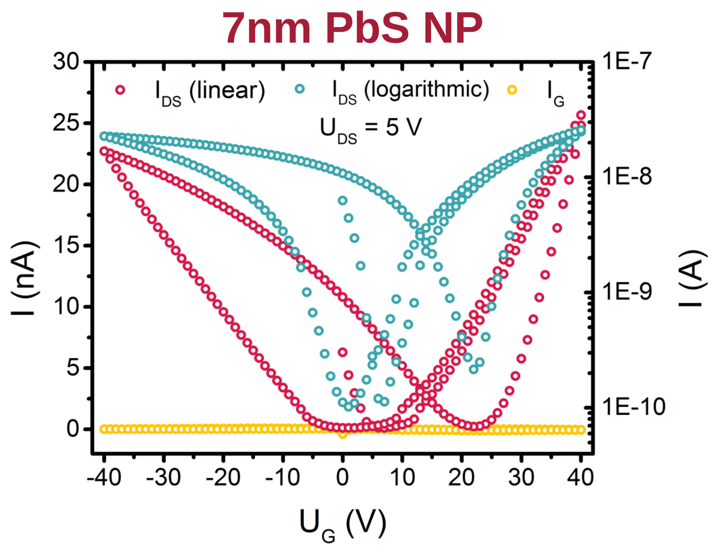
Electrical Gating and Transport Properties

The electrical properties of the COINs were determined from FET measurements (gate sweeps with a constant source-drain voltage of 5V) using different sizes of PbS NP ("electric gating"). COINs with 4 nm PbS NP show mostly electron conductivity whereas COINs with 7 nm PbS NP show ambipolar behavior.

4nm PbS NP



7nm PbS NP



On-off modulation of about 4.5 and 2.5 orders of magnitude for e^- and h^+ conductivity in case of the 4 nm PbS NP and 2.5 orders of magnitude for both charge carriers in case of the 7nm PbS NP were found. Using the gradual channel approximation, charge carrier mobilities $\mu\,[\mathrm{cm^2 (V \cdot s)^{-1}}]$ were calculated. Also charge carrier concentrations $n\,[\mathrm{cm^{-3}}]$ were determined:

$\mu_{e^-} = 3.8 \cdot 10^{-4}, \mu_{h^+} = 4.4 \cdot 10^{-6}$

$n_{e^-} = 1.5 \cdot 10^{14}, n_{h^+} = 1.3 \cdot 10^{16}$

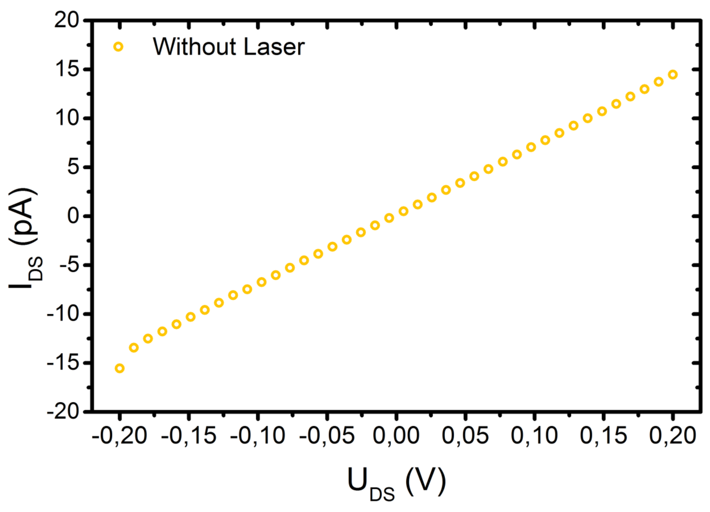
$\mu_{e^-} = 2.9 \cdot 10^{-6}, \mu_{h^+} = 4.0 \cdot 10^{-6}$

$n_{e^-} = 1.8 \cdot 10^{16}, n_{h^+} = 5.8 \cdot 10^{16}$

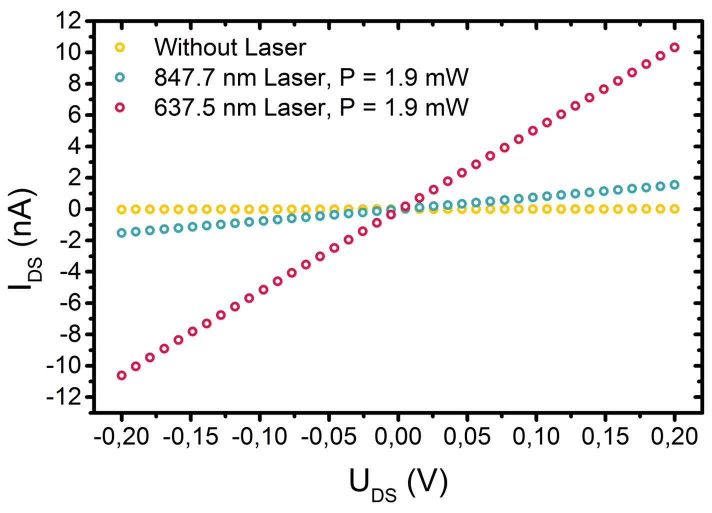
Optical Gating and Photoconductivity

Conductivity measurements with different laser light wavelengths but the same optical power were performed on COIN coated (7 nm PbS NP) FET substrates whereby the complete active area between the contacts was illuminated → optical gating.

Without Laser



637.5 and 847.7 nm Laser



Specific conductivities $\sigma\,[\mathrm{S/cm}]$ were calculated:

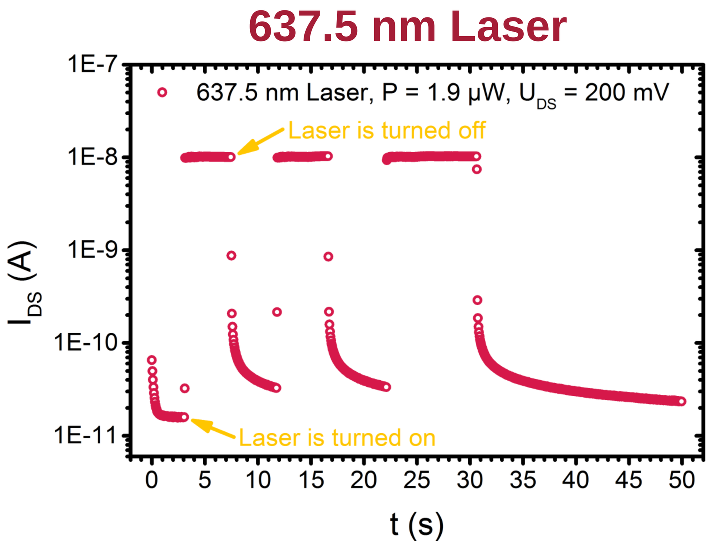
$\sigma_{\text{without laser}} = 6.0 \cdot 10^{-9}$

$\sigma_{637.5\ \text{nm}} = 4.3 \cdot 10^{-6}$

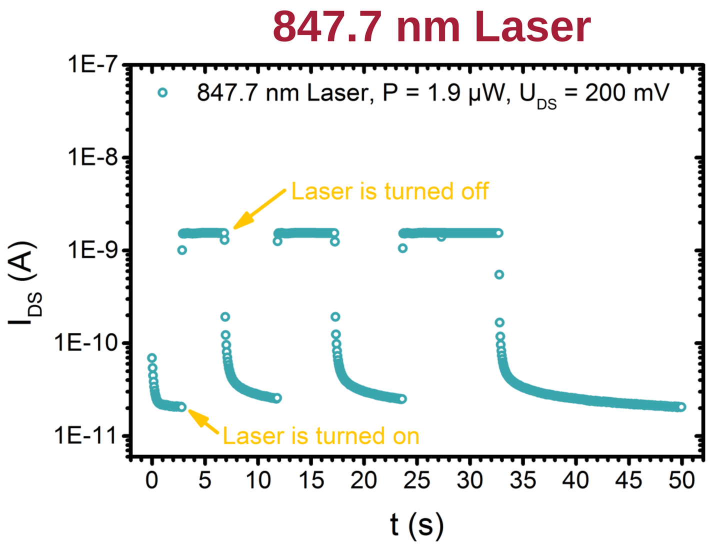
$\sigma_{847.7\ \text{nm}} = 6.4 \cdot 10^{-7}$

Laser-on-off measurements show a fast response of the system towards laser irradiation (50 ms per point). After the laser is turned off, a decay can be observed. In case of the 637.5 nm laser the overall measured current increases almost 3 orders of magnitude under light illumination while for the 847.7 nm laser an increase of almost 2 orders of magnitude can be seen.

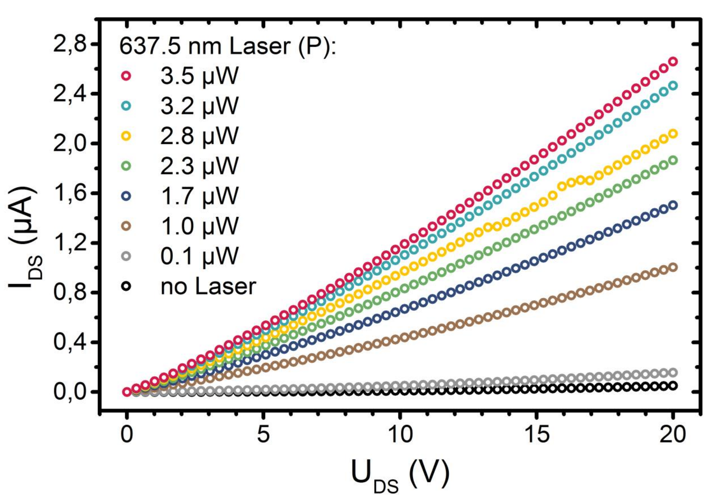
637.5 nm Laser



847.7 nm Laser



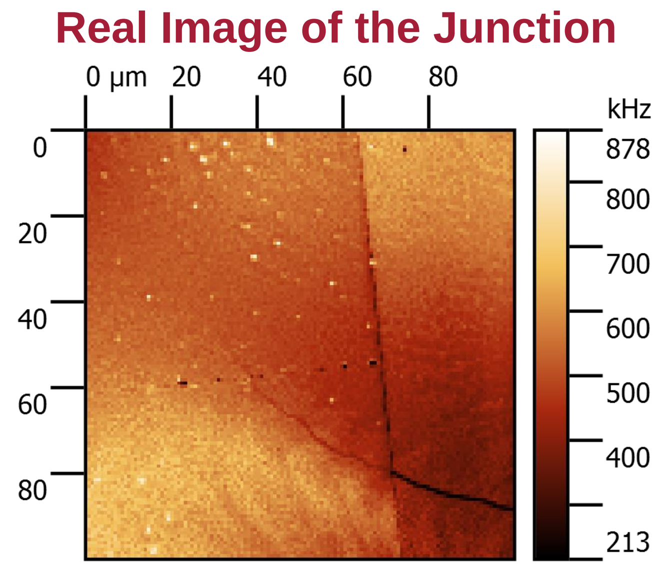
Source-drain I vs. U characteristics with different optical output power at 637.5 nm were studied. Typical saturation behavior like for FETs was not observed. However, with increasing optical power of the laser the measured current also increases. At negative SD voltages the material behaved the same way. With the 847.7 nm laser, the overall currents were smaller.



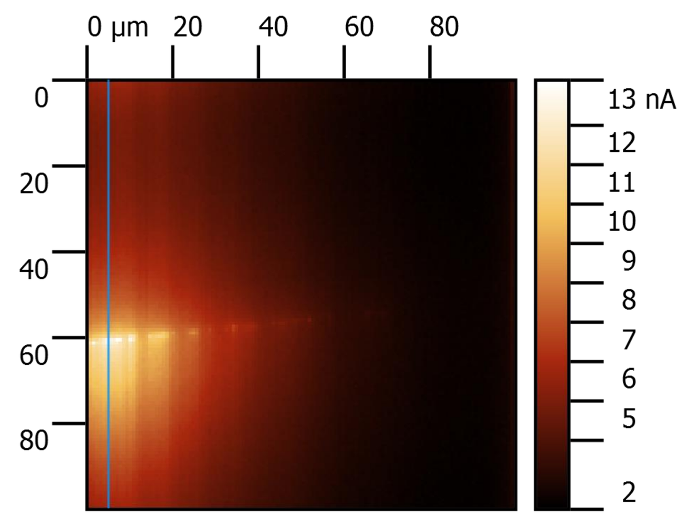
Spatially Resolved Current Measurements Over the Junction

By using an inverse confocal microscope setup equipped with a 630 nm He-Ne laser (500 nm focus) and a 488 nm laser diode (350 nm focus), spatially resolved current measurements were performed over a junction on a COIN coated (7 nm PbS NP) self-made substrate revealing that only illuminating the channel leads to an increase of the measured current.

Real Image of the Junction

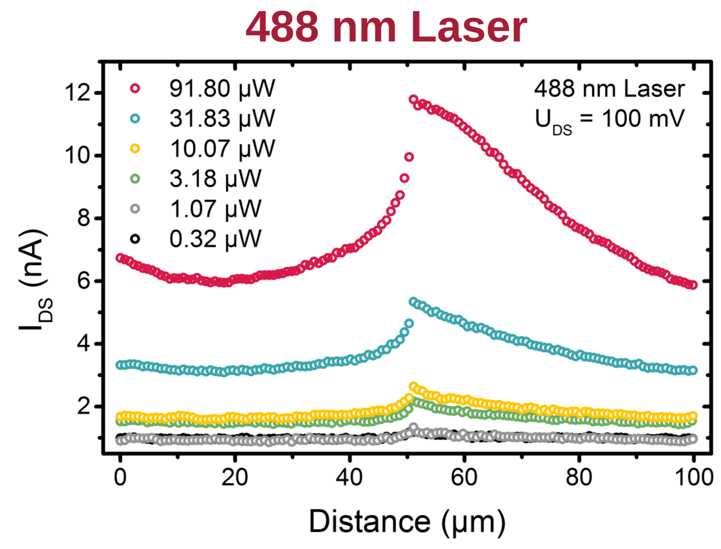


Measured Current

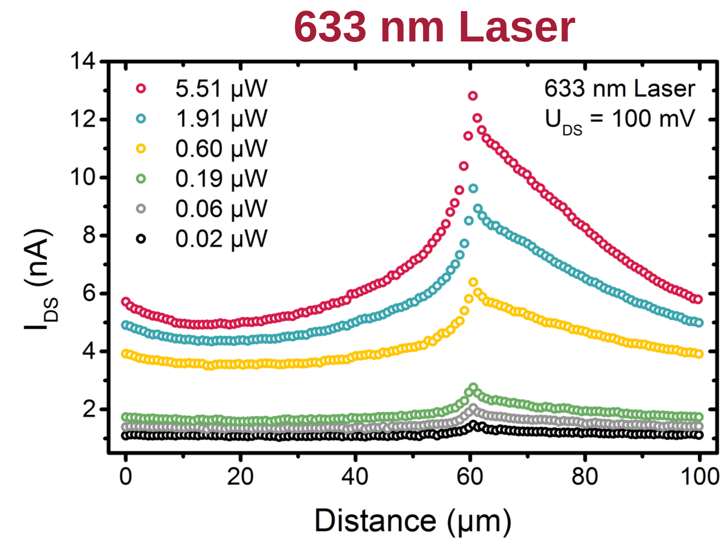


Linecuts (blue line in picture above) of measurements with different optical laser output powers were made showing that the current increase is the same for both lasers while the 488 nm laser operates at a optical power about 16 times higher than the 633 nm laser.

488 nm Laser



633 nm Laser



Conclusion

Thin layers of COINs consisting of PbS NP crosslinked with a polyphenylene-ethynylene derivative were characterized in terms of their electronic properties towards electrical and optical gating. In both cases, a current increase of about the same order of magnitude was observed. Exciting the material at a wavelength of the induced absorption leads to a significant increase of the photocurrent.

References

[1] M. Scheele, W. Bruetting, F. Schreiber, *Phys. Chem. Chem. Phys.* **2015**, *17*, 97–111.

[2] U. H. F. Bunz, *Macromol. Rapid Comm*. 2009, 30, 772-805.