Supporting Information for

Full Alignment of Dispersed Colloidal Nanorods by Alternating Electric Fields

*Mohammad Mohammadimasoudi**[1,3], *Zeger Hens*[2,3], *Kristiaan Neyts*[1,3]

[1]Electronics and Information Systems Department, Ghent University, St. Pietersnieuwstraat 41, 9000 Gent, Belgium

[2]Physics and Chemistry of Nanostructures, Ghent University, Krijgslaan 281-S3, 9000 Gent, Belgium

[3]Center for Nano- and Bio-photonics, Ghent University, St. Pietersnieuwstraat 41, 9000 Gent, Belgium

Content: Synthesis of CdSe/CdS nanorods; Photograph and transmission measurement of CdSe/CdS NR suspension in dodecane; Characteristic information and obtained data on CdSe/CdS NRs; Rotational relaxation frequency; Polarization ratio

Author information
* Corresponding authors: mohammad.mohammadimasoudi@ugent.be, kneyts@elis.ugent.be

S1 Synthesis of CdSe/CdS nanorods

The first step in synthesizing CdSe/CdS dot-in-rods is making CdSe core QDs.[1] They are prepared from a mixture of 0.12 g of CdO, 6 g of trioctylphosphine oxide (TOPO) and 0.56 g of octadecylphosphonic acid (ODPA) which is degassed under vacuum at 120 °C for 1 hour. Next, the mixture is heated to 350 °C under nitrogen atmosphere and a mixture of 0.116 g of Se and 0.72 g of trioctylphosphine (TOP) is quickly injected. The reaction time is adjusted to obtain CdSe QDs with a diameter of 2.3 nm. The reaction is then quenched and the QDs are purified three times by centrifugation, using toluene and isopropanol as the solvent and the non-solvent respectively.The size and concentration of the CdSe QDs are determined from UV-vis absorption measurements, using an already published sizing curve,[2] and extinction coefficient.[3] The CdSe/CdS dot-in-rods are prepared from a mixture of 0.057 g of CdO, 3 g of TOPO, 0.25 g of ODPA and 0.08 g of hexylphosphonic acid (HPA) which is degassed under vacuum at 120 °C for 1 hour. Next, the mixture is heated to 360 °C under nitrogen atmosphere and 1.9 ml of TOP is injected. Subsequently, at the same temperature 0.089 g of sulfur in 1.9 ml of TOP and 70 nmol of the above-mentioned CdSe QDs are injected in the reaction mixture. The reaction is quenched after 8 minutes and the dot-in-rods are purified three times by centrifugation, using toluene and isopropanol as the solvent and the non-solvent respectively. The NRs involved in this work have an average diameter of 4.8 nm and an average length of 51.5 nm as determined by TEM observation (Figure S1). The concentration of the NRs suspension in toluene is estimated from the amount of CdSe seeds, considering that no particle was lost during the process.

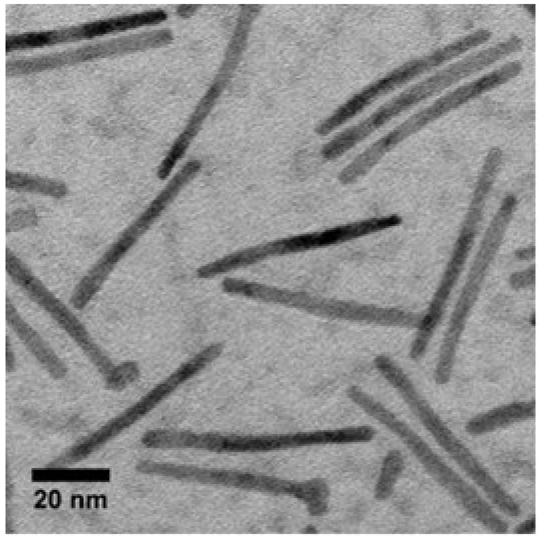

Figure S1. TEM image of the CdSe/CdS dot-in-rods on a cuopper grid coated with a carbon film.

S2 CdSe/CdS quantum rod filled cells

The NRs dispersed in dodecane are infiltrated into the cells (two glass substrates with 1 cm2 ITO electrodes with 50 μm spacing between the electrodes). Figure S2 indicates the aggregation of NRs are negligible for the cell filled with a 1 μM dispersion of NRs in dodecane.

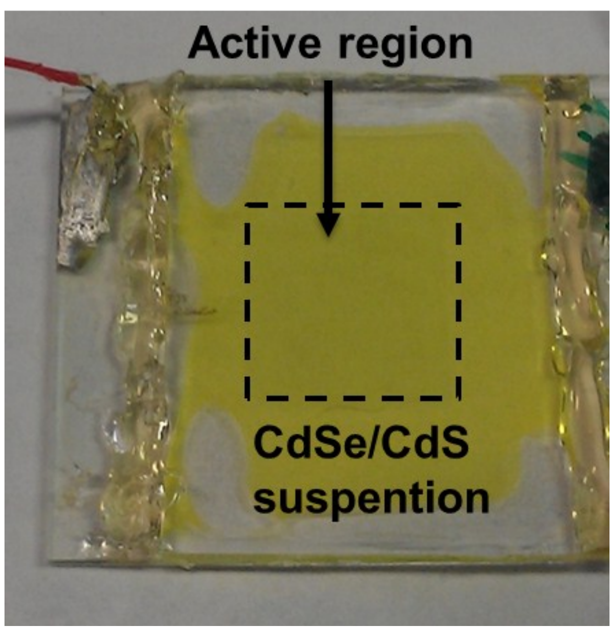

Figure S2. Photograph of the cell filled with a 1 μM dispersion of NRs in dodecane

S3 Transmission measurement of CdSe/CdS NR suspension in dodecane

The transmission of the 50 μm thick cell filled with a 1 μM dispersion of NRs in dodecane at 470 nm is measured in the presence of block wave AC electric fields (17 V/μm, 5 kHz). Figure S3 shows the variation in the transmission of the NRs, together with the applied electric field. The increase in transmission corresponds to a drop of the absorbance. Figure S3 demonstrates that the transmission of the dispersion switches within 100 μs.

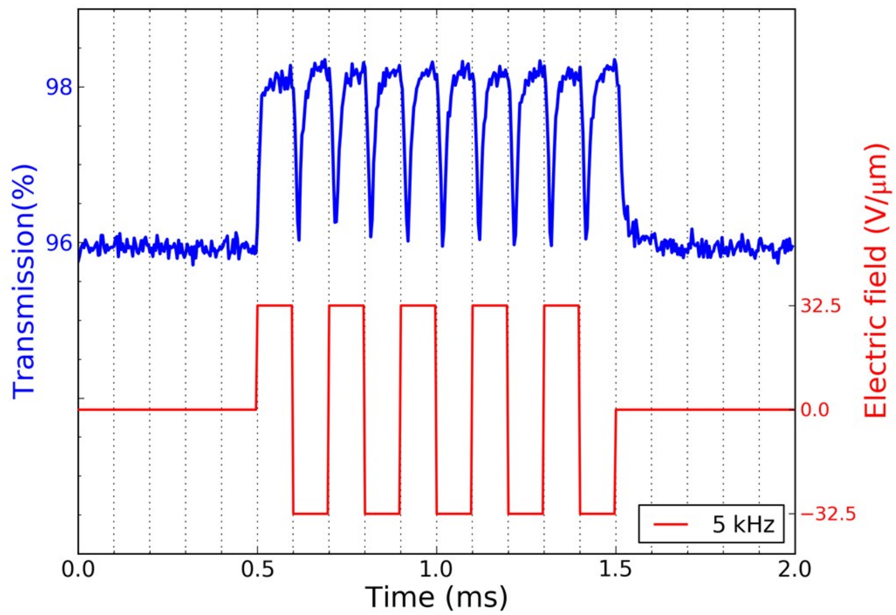

Fig.S3 Transmission measurements (blue dots) of a CdSe/CdS NR suspension for blue light (~470 nm) with and without the presence of a block wave AC electric field with a frequency of 5 kHz and an amplitude of 17 V/μm (red line).

S4 Characteristic information and obtained data on CdSe/CdS NRs

The refractive indices, the relative dielectric constant of CdS and host and the dimension of the CdS/CdSe NRs are required to calculate the anisotropic absorption and the induced dipole moment of the NRs. A number of interesting values for NRs obtained from experimental results are listed in Table S1. The optical constant are listed in Table S2.

Table S1. Obtained experimental and calculated results for CdSe/CdS NRs. The simulated values are obtained from the data in Table S2.

Nanorod dimensions	TEM	Ellipsoid with axes: 51.5 nm; 4.8 nm; 4.8 nm	
Depolarization factor	Eq 3	$L_{\parallel} = 0.018$	$L_{\perp} = 0.49$
Electric field inside CdSe (external field: 20V/ μm)	3D finite element field calculation (comsol)	E ($E_{ext} \parallel$ c-axis) = 18.16 V/μm	E ($E_{ext} \perp$ c-axis) = 8.95 V/μm
Electric field inside CdS (external field: 20V/ μm)	3D finite element field calculation (comsol)	E ($E_{ext} \parallel$ c-axis) = 19.21 V/μm	E ($E_{ext} \perp$ c-axis) = 9.44 V/μm
Dielectric polarizibity	Eq 2	$\alpha_{\parallel} = 2.4*10^{-24}$ m^3	$\alpha_{\perp} = 0.8*10^{-24}$ m^3
Absorption coefficient for 470 nm	Eq 12	$\mu_{\parallel} = 1.8*10^7$ m^{-1}	$\mu_{\perp} = 0.4*10^7$ m^{-1}
Relaxation time of NRs in dodecane	Eq 9	12 μs	
Relaxation frequency of NRs in dodecane	Eq 9	13 kHz	
Typical time to align (τ_{on})	Eq 8	1.6 μs	
Turn on frequency (f_{on})	Eq 8	100 kHz	
Measured permanent dipole moment	Fitted parameter in figure 4b	1500 Debye	
Estimated induced dipole moment at 17 V/μm	Eq 1	100 Debye	
ΔU, the difference in energy between a parallel and a perpendicularly oriented nanoparticle at 17 V/μm	Eq 10	0.57 eV	

Table S2. Optical constant of wurtzite CdS and CdSe at 300 *K*.[4]

Material \ Wavelength		Static value		470 nm		560 nm	
		$E \perp c$	$E \parallel c$	$E \perp c$	$E \parallel c$	$E \perp c$	$E \parallel c$
CdS	n	3	3.2	2.61+ 0.37i	2.70 + 0.39i	2.58	2.59
	ε	8.99	10.21	6.69+ 1.95i	7.12+ 2.18i	6.66	6.72
CdSe	n	3.05	3.19	2.72 + 0.45i	2.75 + 0.48i	2.74 + 0.39i	2.79 + 0.39i
	ε	9.29	10.16	7.20 + 2.47i	7.36 + 2.64i	7.38 + 2.12i	7.62 + 2.20i
Dodecane	n	1.42					
	ε	2.01					

S5 Rotational relaxation frequency

The rotational relaxation frequency of our CdSe/CdS NRs in dodecane is estimated from equation (9) as 13 kHz. Figure S4 demonstrates the transmission follows the time variation of the electric field for frequencies up to 10 kHz.

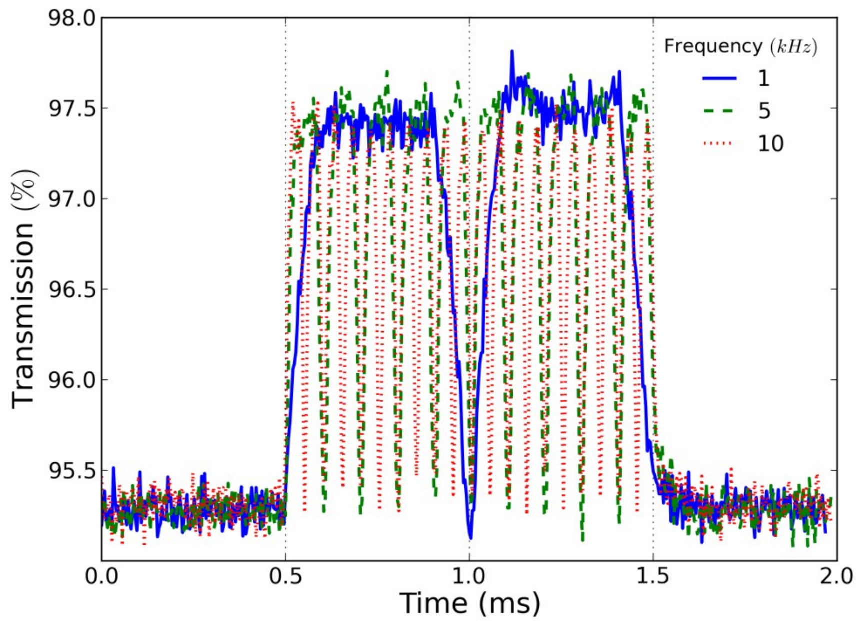

Fig.S4 Transmission of a cell (thickness 50 μm) with CdSe/CdS suspension when an AC electric field is applied with amplitude 17 V/μm and various frequencies

S6 Polarization ratio

The polarization ratio for the emission is defined as: [5]

$$\Pi_r = \frac{(I_{\parallel} - I_{\perp})}{(I_{\parallel} + I_{\perp})} = \frac{(\mu_{\parallel} - \mu_{\perp})}{(\mu_{\parallel} + \mu_{\perp})} \qquad (1)$$

Which $I_{\parallel}$ and $I_{\perp}$ are the corresponded photoluminescent intensities. The polarization ratio is calculated based on absorption coefficients (Table S1) and corresponds to 64%.

References

1. Carbone, L.; Nobile, C.; De Giorgi, M.; Sala, F. D.; Morello, G.; Pompa, P.; Hytch, M.; Snoeck, E.; Fiore, A.; Franchini, I. R.; Nadasan, M.; Silvestre, A. F.; Chiodo, L.; Kudera, S.; Cingolani, R.; Krahne, R.; Manna, L. *Nano Lett.* **2007,** 7, (10), 2942-2950.
2. Jasieniak, J.; Smith, L.; Embden, J. v.; Mulvaney, P.; Califano, M. *J. Phys. Chem. C* **2009,** 113, (45), 19468-19474.
3. Gomes, R.; Hassinen, A.; Szczygiel, A.; Zhao, Q.; Vantomme, A.; Martins, J. C.; Hens, Z. *J. Phys. Chem. Lett.* **2011,** 2, (3), 145-152.
4. Adachi, S., *Optical Constants of Crystalline and Amorphous Semiconductors*. Springer US: 1999.
5. Persano, A.; De Giorgi, M.; Fiore, A.; Cingolani, R.; Manna, L.; Cola, A.; Krahne, R. *ACS Nano* **2010,** 4, (3), 1646-1652.