
Supplementary information

Electroluminescence from nanocrystals above 2 μm

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Supplementary Information: Electroluminescence from Nanocrystals above 2 μm

Junling Qu¹, Mateusz Weis², Eva Izquierdo¹, Simon Gwénaél Mizrahi², Audrey Chu¹,
Corentin Dabard^{1,3}, Charlie Gréboval¹, Erwan Bossavit¹, Yoann Prado¹, Emmanuel
Péronne², Sandrine Ithurria³, Gilles Patriarche⁴, Mathieu G. Silly⁵, Grégory Vincent⁶,
Davide Boschetto², Emmanuel Lhuillier^{1*}

¹ Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP, 75005 Paris, France.

² LOA, ENSTA Paris, Ecole Polytechnique, CNRS, Institut Polytechnique de Paris, 181 Chemin de la Hunière et des Joncherettes 91120 Palaiseau, France.

³ Laboratoire de Physique et d'Etude des Matériaux, ESPCI-Paris, PSL Research University, Sorbonne Université Univ Paris 06, CNRS UMR 8213, 10 rue Vauquelin 75005 Paris, France.

⁴ Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, C2N, Palaiseau 2110, France.

⁵ Synchrotron-SOLEIL, Saint-Aubin, BP48, F91192 Gif sur Yvette Cedex, France.

⁶ ONERA - The French Aerospace Lab, 6, chemin de la Vauve aux Granges, BP 80100, 91123 Palaiseau, France.

*To whom correspondence should be sent: el@insp.upmc.fr

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SUPPLEMENTARY INFORMATION

Supplementary Methods

Chemicals: Mercury chloride (HgCl_2 , Sigma Aldrich, 99%), tellurium powder (Te, Sigma-Aldrich, 99.99%), oleylamine (OLA, Acros, 80-90%), dodecanethiol (DDT, Sigma-Aldrich, 98%), trioctylphosphine (TOP, Cytek, 90%), lead oxide (PbO , Strem Chemicals, 99.999+%), hexamethyldisilathiane ($(\text{TMS})_2\text{S}$, Sigma-Aldrich, synthesis grade), oleic acid (OA, Alfa Aesar 90%), octadecene (ODE, Acros Organics, 90%), zinc acetate dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$, Alfa Aesar, >97%), potassium Hydroxide (KOH, Sigma, $\geq 85\%$), Butylamine (Alpha, 99%), 3-mercaptopropionic acid (MPA, Sigma-Aldrich, $\geq 99.9\%$), 1,2 Ethanedithiol (EDT, Fluka, 98%), chloroform (Carlo Erba), ethanol absolute anhydrous (Carlo Erba, 99.9%), methanol (Carlo Erba, 99.8%), toluene (Carlo Erba, 99.3%), acetonitrile (Sigma-Aldrich, $\geq 99.9\%$), hydrochloric acid (HCl, Mieuxa, 25%). All chemicals are used as received, except oleylamine which is centrifuged before used. **Mercury and lead compounds are highly toxic. Handle them with special care.**

1 M TOP:Te precursor: 2.54 g of Te powder was mixed with 20 mL of TOP in a three-neck flask. The flask was kept under vacuum at room temperature for 5 min before the temperature was raised to 100 °C. Degassing was conducted at this temperature for 20 min. Next, the atmosphere was switched to N_2 and the temperature was raised to 275 °C. The solution was stirred until a clear orange coloration was obtained. The flask was then cooled down to room temperature and the color turned to yellow. Finally, this solution was transferred to a nitrogen-filled glove box for storage.

ZnO nanoparticles: In a 100 mL three-neck flask, Zinc acetate dihydrate (0.98 g) was dissolved in 42 ml of methanol under vigorous stirring and the temperature of the solution was set at 60 °C. In another vial, 0.49 g of KOH were dissolved in 22 ml of methanol. The KOH solution was added dropwise to the zinc acetate solution during 4 min at 60 °C. The reaction mixture was kept under the same conditions for the next 2.5 h. In the end, the heating mantle was removed, and the whitish solution was cooled down to room temperature naturally. The reaction product was separated into two centrifuge tubes and centrifuged at 6000 rpm for 2 min. After trashing the supernatant, equal amount of methanol was added to mix with the pellet before another centrifugation was conducted. After three rounds of purification, half of the ZnO nanoparticles were dispersed in a butylamine/chloroform (1:49 by volume) solution at a concentration of $30 \text{ mg} \cdot \text{mL}^{-1}$, while another half was dispersed in a butylamine/toluene (1:19 by volume) solution at a concentration of $40 \text{ mg} \cdot \text{mL}^{-1}$. The ZnO dispersions were filtered through 0.22 μm PTFE filter before use.

PbS nanocrystal synthesis: 0.94 g of PbO were introduced into a 100 mL three-neck flask with 4 g of OA and 20 g of ODE. The mixture was degassed under vacuum at 110 °C

for 1 hour. Meanwhile, in an air-free glove box, a mixture with 720 μL of $(\text{TMS})_2\text{S}$ and 20 mL of ODE was prepared in a 20 mL vial. The atmosphere of the flask was switched to Ar and the temperature was kept at 110 $^{\circ}\text{C}$. 10 mL of the $(\text{TMS})_2\text{S}$ solution was quickly injected and the solution turned dark immediately. After 1 min, the reaction was stopped by removing the heating mantle and promptly cooling of the flask using a water bath. The nanoparticles were then precipitated by ethanol. The formed pellet was redispersed in toluene. A second step of cleaning was conducted. Finally, the pellet was redispersed in toluene with a 50 mg.mL^{-1} concentration. The solution was centrifuged to remove any colloiddally unstable material. Finally, the solution was filtered with a 0.22 μm PTFE filter.

Field effect transistor: fabrication and characterization

Electrodes fabrication for transistor: A polished Si/SiO₂ substrate was first rinsed and then sonicated in acetone for 5 min. The wafer was then rinsed with acetone and isopropanol, dried with a N₂ flow and finally was cleaned with an O₂ plasma for 5 min. Then, AZ 5214E resist was spin coated on the substrate and baked at 110 $^{\circ}\text{C}$ for 90 s. The resist was exposed through a shadow mask to UV illumination for 1.5 s. The resist was baked again at 125 $^{\circ}\text{C}$ for 2 min and re-exposed to UV (without the mask) for 40 s. The resist was then developed using AZ726 for 30 s. The film was rinsed with water and dried. The remaining organic layer was removed by plasma cleaning. 5 nm of chromium and 80 nm of gold were evaporated, and the remaining resist was removed by immersing the film in acetone for one hour. The electrodes were then rinsed with isopropanol and finally dried. The interdigitated electrodes include 25 pairs of digits, each 2.5 mm long with a 20- μm gap between them. The optical area of the device is 0.037 cm^2 .

Electrolyte gating: For electrolyte gating we first mixed in a glove box 0.5 g of LiClO₄ with 2.3 g of PEG ($M_w = 10 \text{ kg.mol}^{-1}$). The vial was then heated at 170 $^{\circ}\text{C}$ on a hot plate for 2 h until the solution turned clear. The electrolyte solution was warmed to around 100 $^{\circ}\text{C}$ and brushed on the top of the NC film.

Thin film deposition and ligand exchange: The thin films for transport measurement were deposited onto an interdigitated electrode by spin coating. The 30 mg.mL^{-1} solution prepared for the LED fabrication was used. After the spin coating of the first layer, the sample was dipped in a 0.1% MPA solution in methanol for 1 min to allow the ligand exchange. Then the film was rinsed in methanol for 30 s. The above process was repeated once more to fill the cracks induced by the previous ligand exchange. The overall thickness of the film was 60-80 nm.

Transistor measurement: The sample was connected to a Keithley 2634b source meter, which set the drain source bias (V_{DS}), controlled the gate bias (V_{GS}) with a step of 1 mV and measured the associated currents (I_{DS} and I_{GS}).

LED characterization

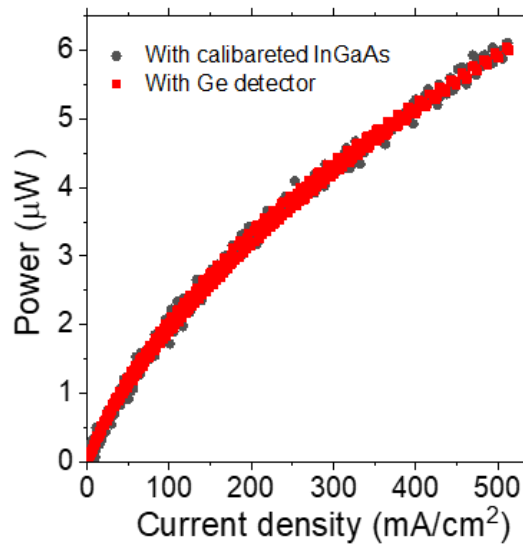
Current-Voltage-Radiance characteristics of the LED was probed with a Keithley K2450 that collect the current-voltage of the LED, and a Keithley 2400 coupled with an DET10D/M extended InGaAs detector.

The calibration of photon power from InGaAs detector: By connecting the InGaAs detector to a source meter with a coaxial cable, we can directly read its output voltage (V_{out}), which is assumed to be linear to the incident power $P(\lambda)$ at a wavelength of λ . Thus, the relation between the power and V_{out} can be described as:

$$P(\lambda) = C \cdot \frac{V_{out}}{R(\lambda)}$$

Where C is a constant related to the geometry of the detector and the device, and $R(\lambda)$, in $A W^{-1}$, represents the responsivity of InGaAs detector at the wavelength of λ . To determine the value of C , we used a HgTe-LED emitting at around $1.3 \mu m$ as a reference, and measured the same device with both Ge 122C (I-V-power) and InGaAs detector (I-V- V_{out}). Taking the responsivity of InGaAs at $1.3 \mu m$ as $0.45 A.W^{-1}$, we found that when $C = 7.15 \times 10^{-4}$, the two measurements overlap, see **Supplementary Figure 1**. This relation can be generalized to λ beyond the Ge range. Thus, we can determine the power of our $2-2.3 \mu m$ LED by taking the corresponding $R(\lambda)$, which is between 1.2 and $1.3 A.W^{-1}$.

$$P(\lambda) = 7.15 \times 10^{-4} \cdot \frac{V_{out}}{R(\lambda)}$$



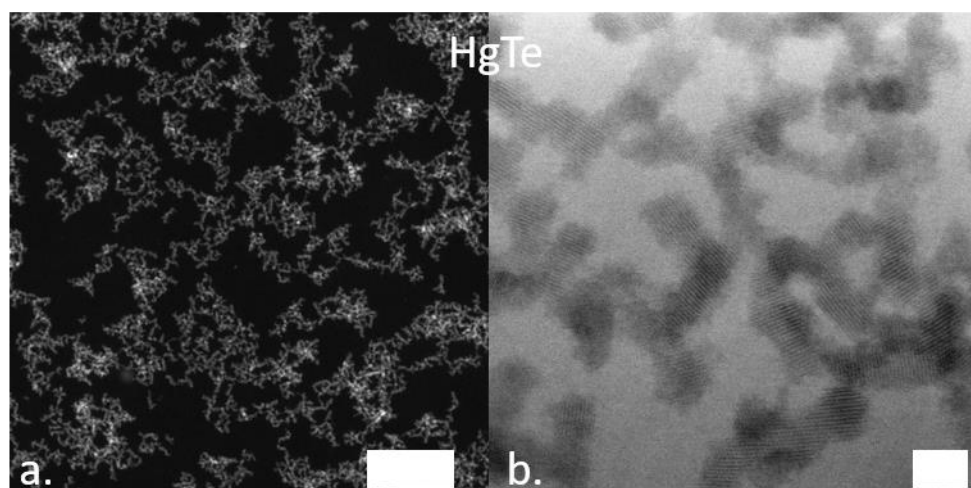
Supplementary Figure 1: Photon power obtained by a S122C Ge detector (red scatters) and the power calibrated from InGaAs detector (black scatters) as a function of current density. The data are based on the same HgTe-LED emitting at $1.3 \mu m$.

Operational lifetime measurement: During the lifetime measurement, the LED was driven at a constant current which corresponds to an initial radiance of $1 W Sr^{-1}m^{-2}$. The change of radiance (power) with time was monitored with the InGaAs detector.

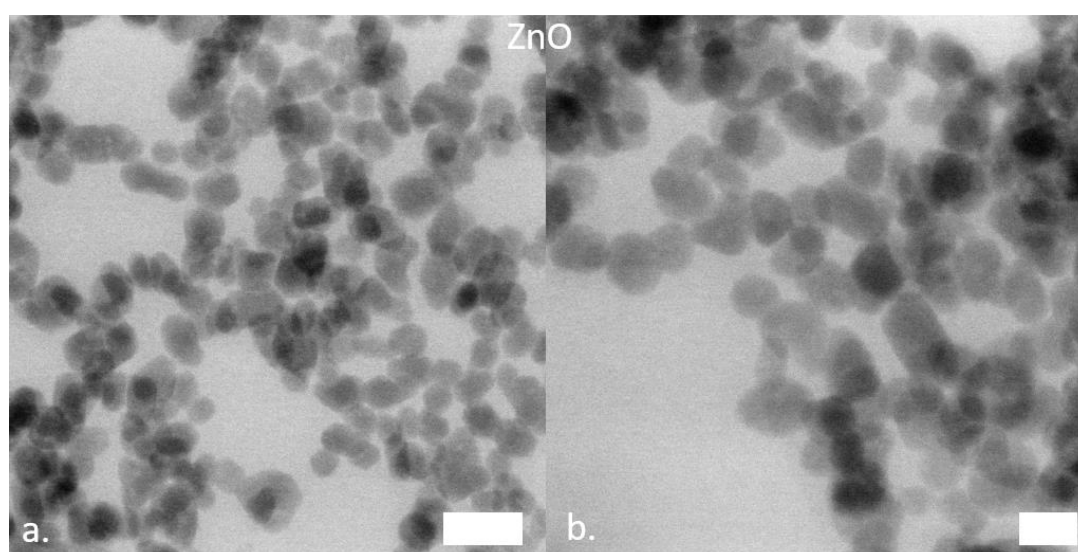
Imaging Diode: A NOXCAM 640M-HSI camera was used to take Infrared pictures of the LED. The integration time was set as 1 ms. A reference for uniformity was made by putting a uniform absorbing material close to the objective of the camera. The auto adjust was turned off. Different filters were placed in front of the camera (see Supplementary Figure 14 for the filter spectra).

Supplementary note 1: Electron microscopy of HgTe, ZnO NCs and their mixture

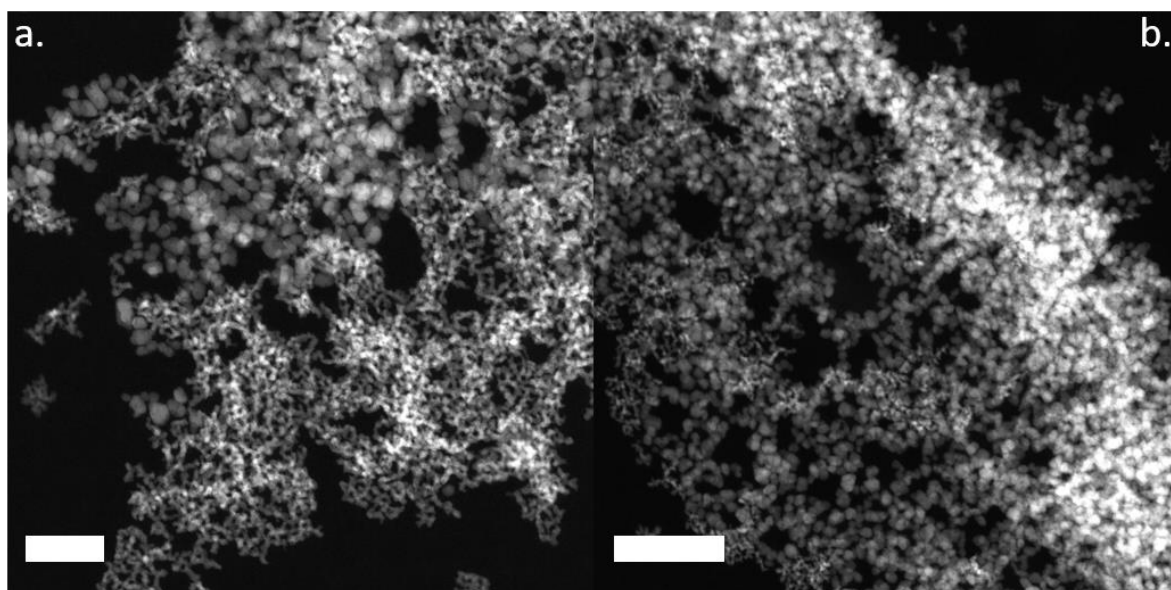
Supplementary Figure 2 – Supplementary Figure 4 show the transmission electron microscopy of HgTe (Supplementary Figure 2), ZnO (Supplementary Figure 3) and their mixture (Supplementary Figure 4). HgTe NCs present multipodic aspects, while ZnO NCs present a shape between spheres and cubes. ZnO NCs are also larger, which makes the two types of particles easy to discriminate in the mixture. To further discriminate the two materials, we also use energy dispersive X-ray imaging coupled to electron microscopy image (Supplementary Figure 5). There is inhomogeneity at the few tens of nm scale but material appears homogenous at the scale of the pixel ($1 \times 1 \text{ nm}^2$).



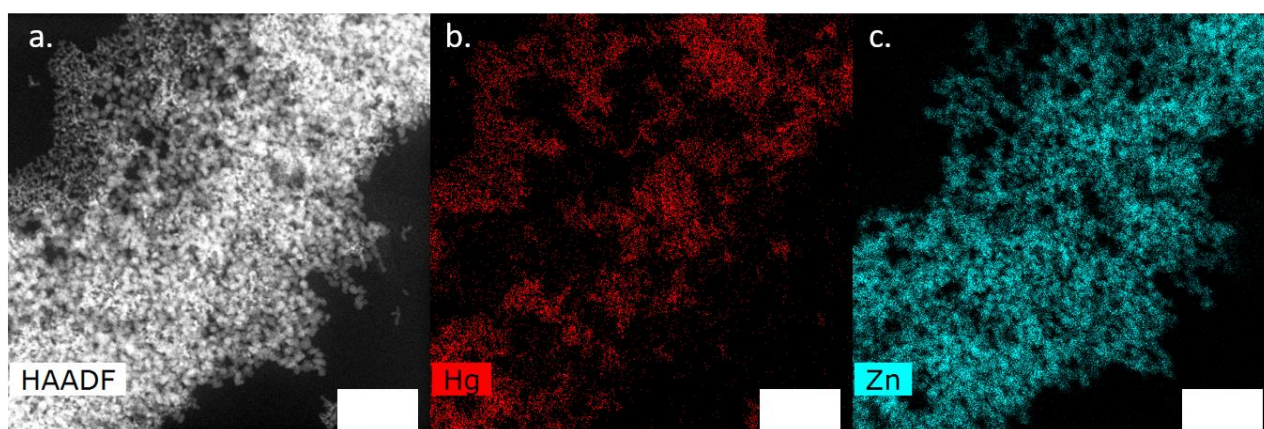
Supplementary Figure 2: (a) STEM-HAADF images of HgTe NCs with a photoluminescence emission peak at $2 \mu\text{m}$. (b) High resolution TEM image of the same nanocrystals. Scale bars are respectively 50 nm and 5 nm for part a and b.



Supplementary Figure 3: Low (a) and high (b) resolution STEM-HAADF images of ZnO NCs. Scale bars are respectively 20 nm and 10 nm for part a and b.



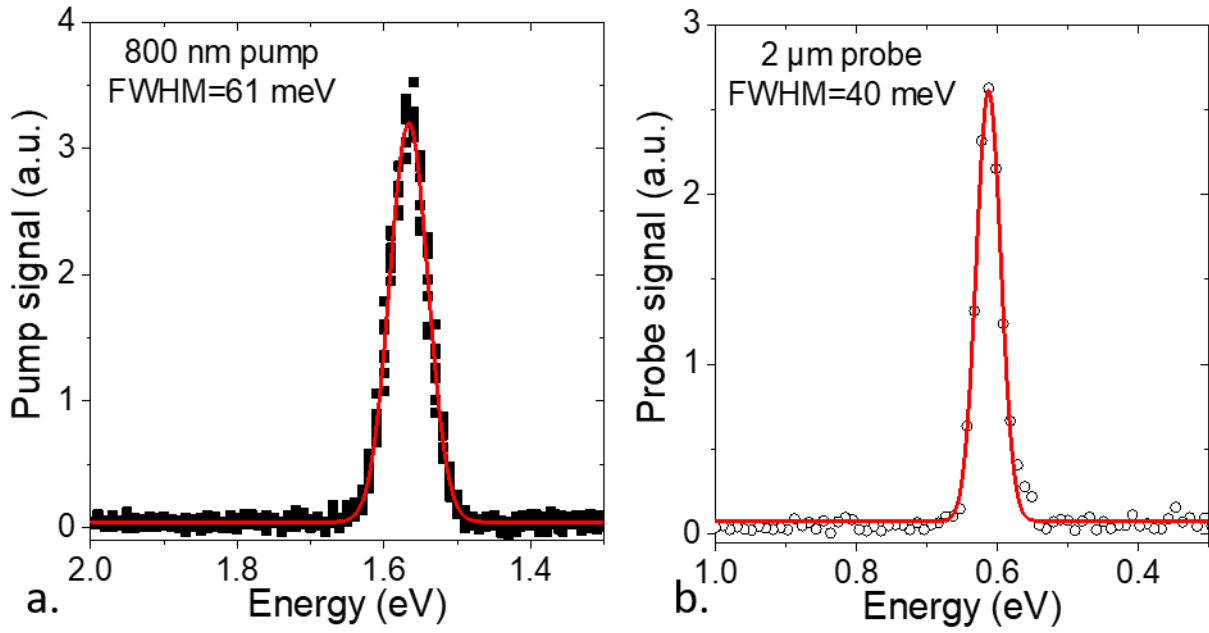
Supplementary Figure 4: STEM-HAADF images of the ZnO:HgTe mixture. Scale bars are respectively 50 nm and 100 nm for part **a** and **b**.



Supplementary Figure 5: Scanning transmission electron microscopy image of ZnO:HgTe mixture (**a**) and Hg (**b**) and Zn (**c**) EDX mapping on the same area. Scale bars are 100 nm for all parts.

Supplementary note 2: Transient reflectivity

The laser pulses being short, they are spectrally broad. For a 35-fs pulse duration, the quantum limit leads to $\Delta E \approx \hbar/\Delta\tau = 18$ meV. Experimentally, we observed laser pulses that are slightly above this limit and find a full width at half maximum of 60 meV for the pump and around 40 meV for the probe, see **Supplementary Figure 6**. These broadening have to be compared with the charging energy E_c of a nanocrystal given by $E_c = \frac{e^2}{4\pi\epsilon_r\epsilon_0 R} = 22$ meV if we assume $\epsilon_r = 16$ as the dielectric constant of HgTe, and where $R = 4$ nm is the particle radius, e the proton charge, and ϵ_0 the vacuum permittivity and to the thermal energy $k_b T = 25$ meV at room temperature. Thus, we can neglect coulombic shift in the analysis of the transient reflectivity which is mostly driven by state filling in this configuration.

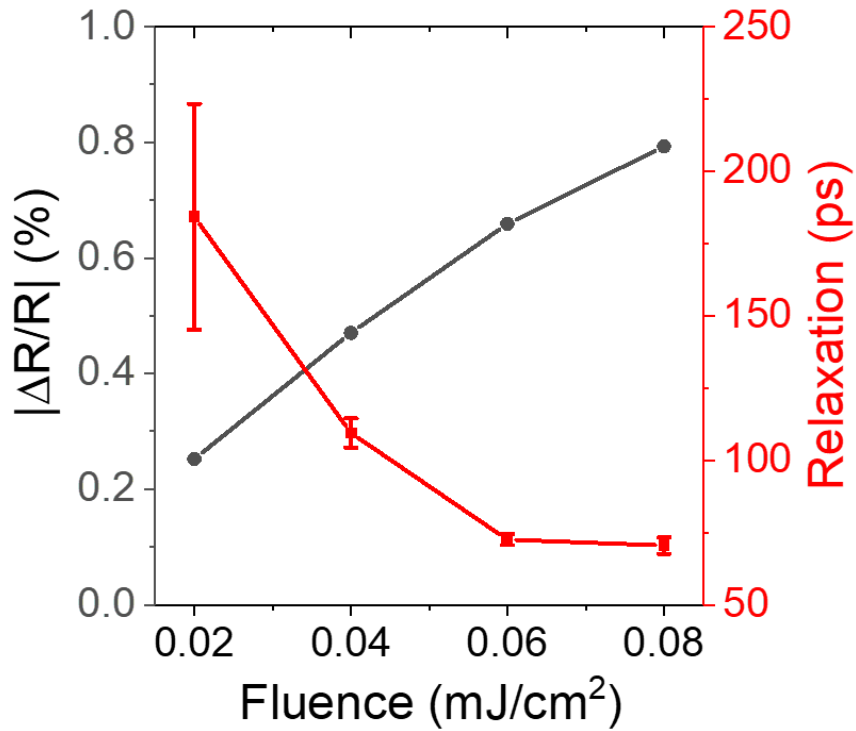


Supplementary Figure 6: Spectral characterization of the pump and probe used for transient reflectivity.

The decay of the transient reflectivity signal associated with the regime III, see figure 1e, present a clear fluence dependence. The larger the flux the shorter the decay time, see Supplementary Figure 7.

According to Rastogi *et al*², the extinction coefficient of HgTe NC film at the exciton is $k = 0.1$. The latter relates to the absorption coefficient α through $\alpha = 4\pi k / \lambda$ where λ is the wavelength. The absorption coefficient also relates to the absorption cross section $\alpha = \sigma \eta / V_{NC}$ with V_{NC} the volume of a NC and η the volume fraction of the film, taken here as 0.64 assuming a random close packing. This leads to $\sigma = \frac{4\pi k V_{NC}}{\lambda \eta} = 2 \times 10^{-15} \text{ cm}^2$. We use in the Figure 2 experiment a fluence of $60 \mu\text{J} \cdot \text{cm}^{-2}$ (the value is tuned between 20 and 80 in **Supplementary Figure 7**) which corresponds to $6 \times 10^{14} \text{ photons} \cdot \text{cm}^{-2}$. This generates 1.2 electron hole pair(s) /nanocrystal. Thus, in the high part of the chosen fluence range,

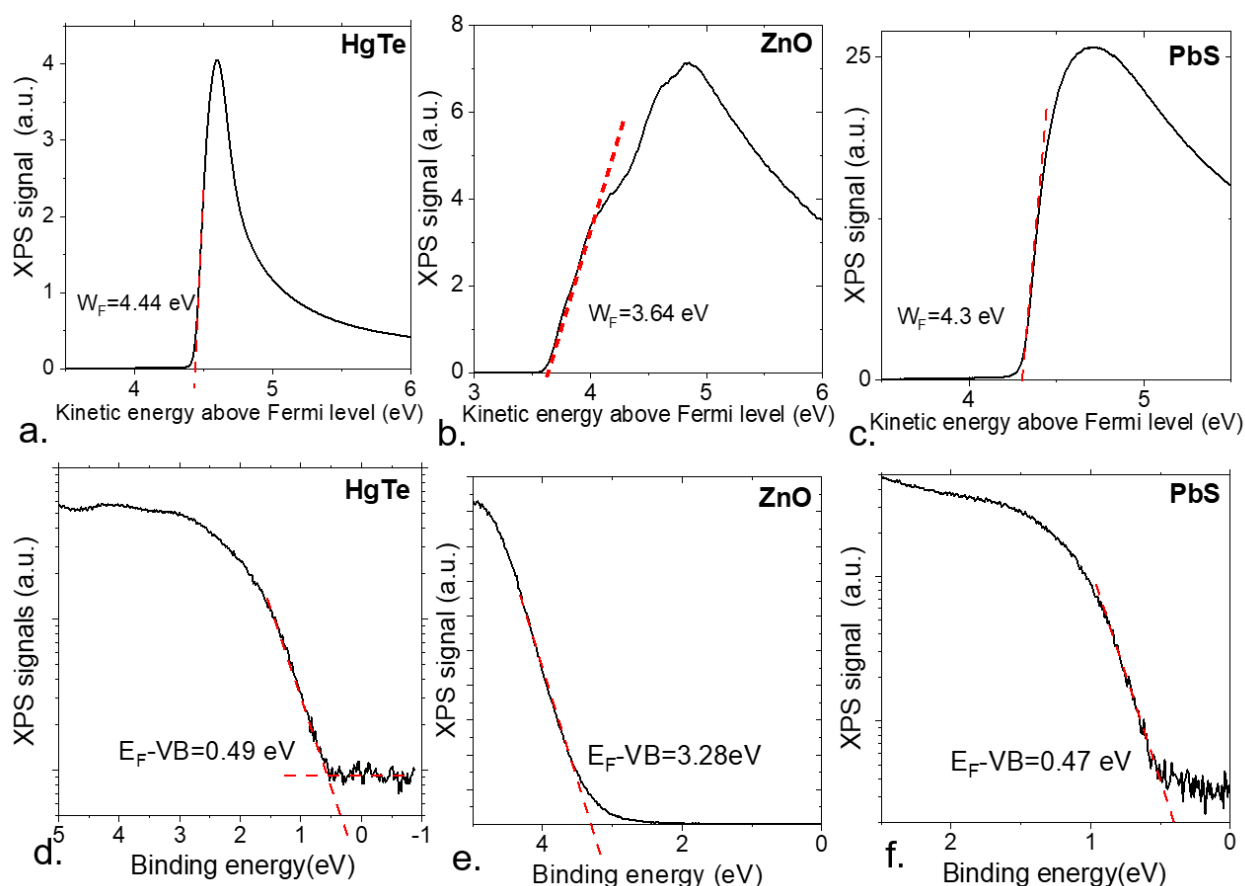
multiexcitonic effects are expected and the fastening of the response can be associated to Auger effect.



Supplementary Figure 7: Amplitude and relaxation time of the transient reflectivity signal as a function of the pump fluence for a HgTe thin film. The relaxation time has been estimated by a first-order development of the exponential-like relaxation.

Supplementary note 3: Band alignment in LED

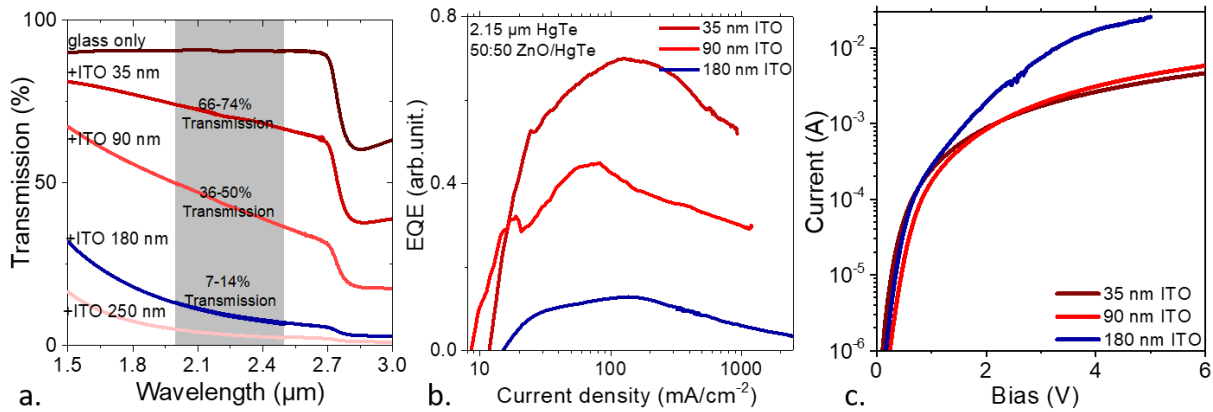
X-ray photoemission is used to determine the energy of valence band, conduction band, and Fermi level with respect to the vacuum level. The energy of the Fermi level is first determined using the cut-off of the secondary electron, see Supplementary Figure 8a-c. The lowest binding energy part of the photoemission spectrum is used to unveil the relative energy of the valence band with respect to the Fermi level. Finally, the conduction band is positioned with respect to the valence band using the optical band gap value. No excitonic corrections are considered here.



Supplementary Figure 8: X-ray photoemission spectra relative to the cut-off of the secondary electrons for HgTe (a), ZnO (b) and EDT-capped PbS (c) nanocrystal films. X-ray photoemission spectra relative to the valence band of HgTe (d), ZnO (e) and EDT-capped PbS (f) nanocrystal films.

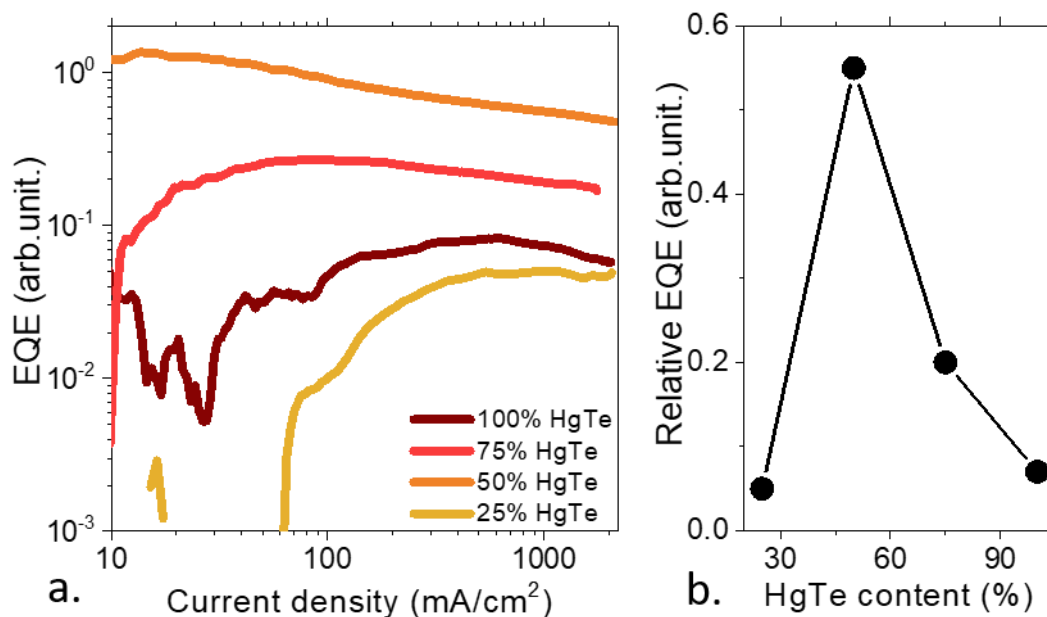
Supplementary note 4: Effect of the transparent conductive oxide thickness³

As the emitting wavelength of the LED is redshifted, its transmission through the ITO layer is reduced, see Supplementary Figure 9a. Thus, using a thinner ITO layer enable better photon extraction and improve the EQE of a 2.15 μm emitting LEDs (Supplementary Figure 9b), even if the devices are more resistive (Supplementary Figure 9c).



Supplementary Figure 9: **a** Transmission of ITO thin films on a glass substrates as a function of wavelength; the ITO film thickness ranges from 35 nm to 250 nm. **b** Uncalibrated EQE as a function of injected current density for LEDs based on identical structure but different ITO thickness; the emitting layer is made of HgTe(50%):ZnO emitting at 2.15 μm . **c** Current-voltage characteristics of the LEDs described in **b**.

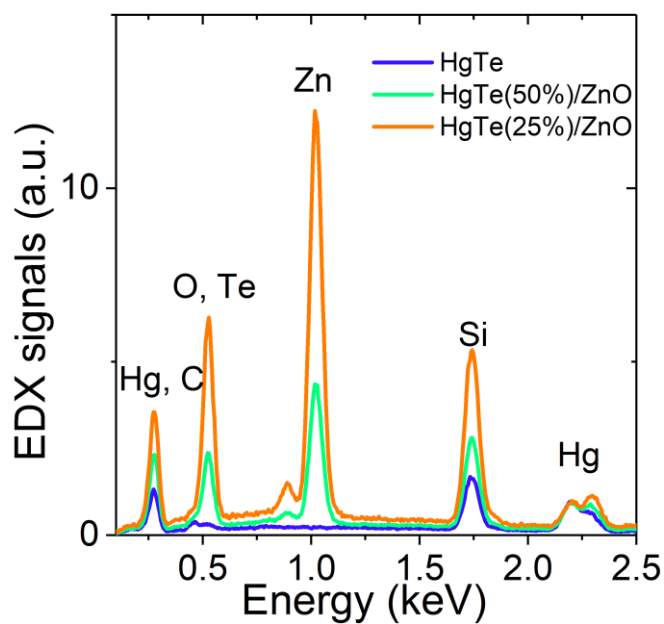
Supplementary note 5: Effect of the HgTe:ZnO content of the emissive layer on LED performance.



Supplementary Figure 10: **a** Uncalibrated EQE as a function of applied current density for 2 μm LEDs with emissive layer made of pure HgTe and mixture of HgTe:ZnO with 75, 50 and 25 % of HgTe volume ratio. **b** Relative EQE at a current density of 1000 mA cm^{-2} for the LEDs described in **a**. Note that all the LEDs here for comparison are built using 180 nm ITO.

The benefit of mixing the HgTe emissive layer with ZnO is depicted in Supplementary Figure 10. Optimal EQE corresponds to a mixture of 50% volume of the two solutions.

With energy dispersive X-ray spectroscopy (see Supplementary Figure 11), the atomic ratio of Hg/Zn can be determined for various HgTe:ZnO films with different HgTe content, as shown in Supplementary Table 1. The size of HgTe nanocrystal is evaluated by taking its shape as a tripod of three cylinders. From TEM images, the diameter and the height of each cylinder are determined as 3.6 nm and 6 nm, respectively, which means each HgTe tripod contains 2730 HgTe molecules. Using X-ray diffraction, the diameter of ZnO NCs used in the HgTe:ZnO mix is determined to be 8.3 nm, which means there are 4180 ZnO molecules in a single ZnO nanoparticle.¹ Combining the atomic ratio of Hg/Zn in the film, and the number of HgTe and ZnO molecules in a single nanocrystal, we can calculate the ratio of HgTe tripod/ZnO nanoparticle for the HgTe:ZnO mixture film. As presented in Supplementary Table 1, for HgTe(50%):ZnO film, there are 4.4 ZnO nanoparticles respective to 1 HgTe tripod, whereas for HgTe(25%):ZnO film, there are 8.4 ZnO nanoparticles respective to 1 HgTe tripod.



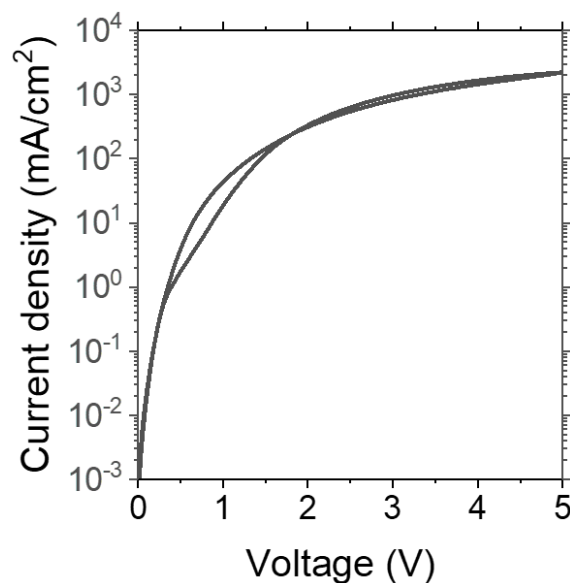
Supplementary Figure 11: Energy dispersive X-ray spectroscopy for films made of HgTe, HgTe(50%):ZnO and HgTe(25%):ZnO.

Supplementary Table 1: Atomic and nanocrystal ratio for HgTe (50%):ZnO and HgTe (25%):ZnO.

Film composition	Hg atom (%)	Zn atom (%)	Zn/Hg atomic ratio	ZnO/HgTe NC ratio
HgTe(50%):ZnO	2.8	18.45	6.7	4.4
HgTe(25%):ZnO	1.78	22.94	12.9	8.4

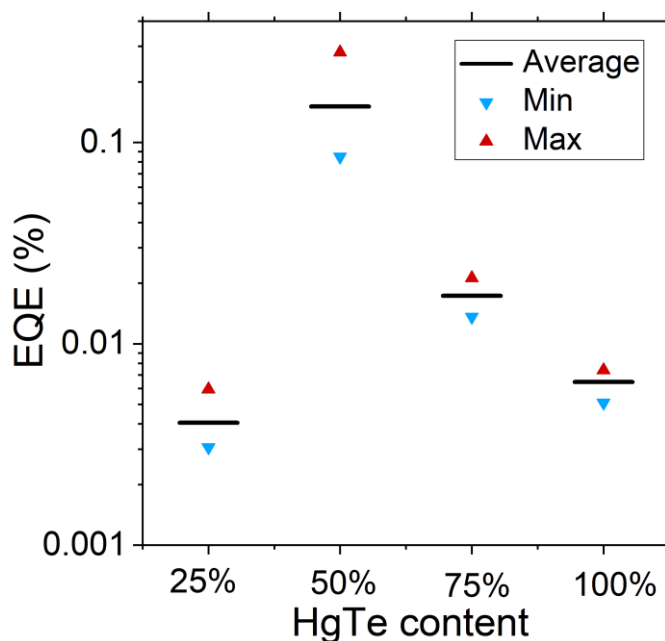
Supplementary note 6: Reproducibility of the performance

The LED presents a limited hysteresis in the IV curve, see **Supplementary Figure 12**.



Supplementary Figure 12: IV curve of the LED using 2 μm emitting HgTe NCs while the bias is sweep up and down.

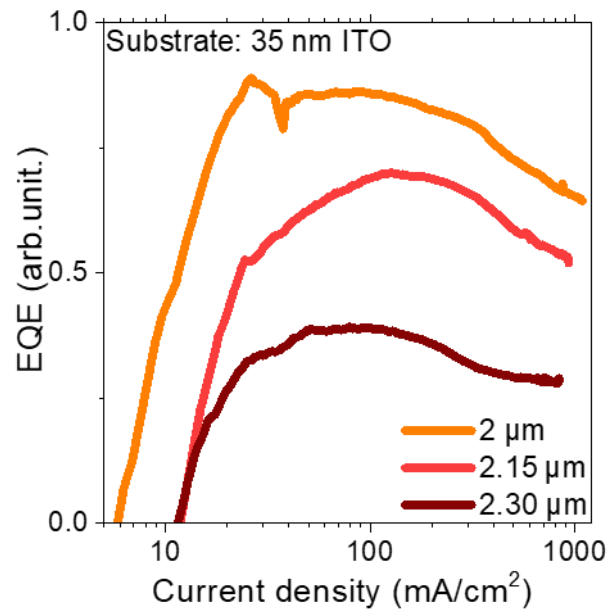
The reproducibility of the LED performances has been tested for LEDs with various ZnO content, see Supplementary Figure 13.



Supplementary Figure 13: EQE statistics for 2 μm LEDs using different HgTe contents in the HgTe:ZnO emitting layer, with the center line the average, the red triangles the maximum and the blue triangles the minimum values of the calibrated EQE. The average values are obtained from around 10 LED devices.

Supplementary note 7: Effect of the peak emission wavelength on LED performance

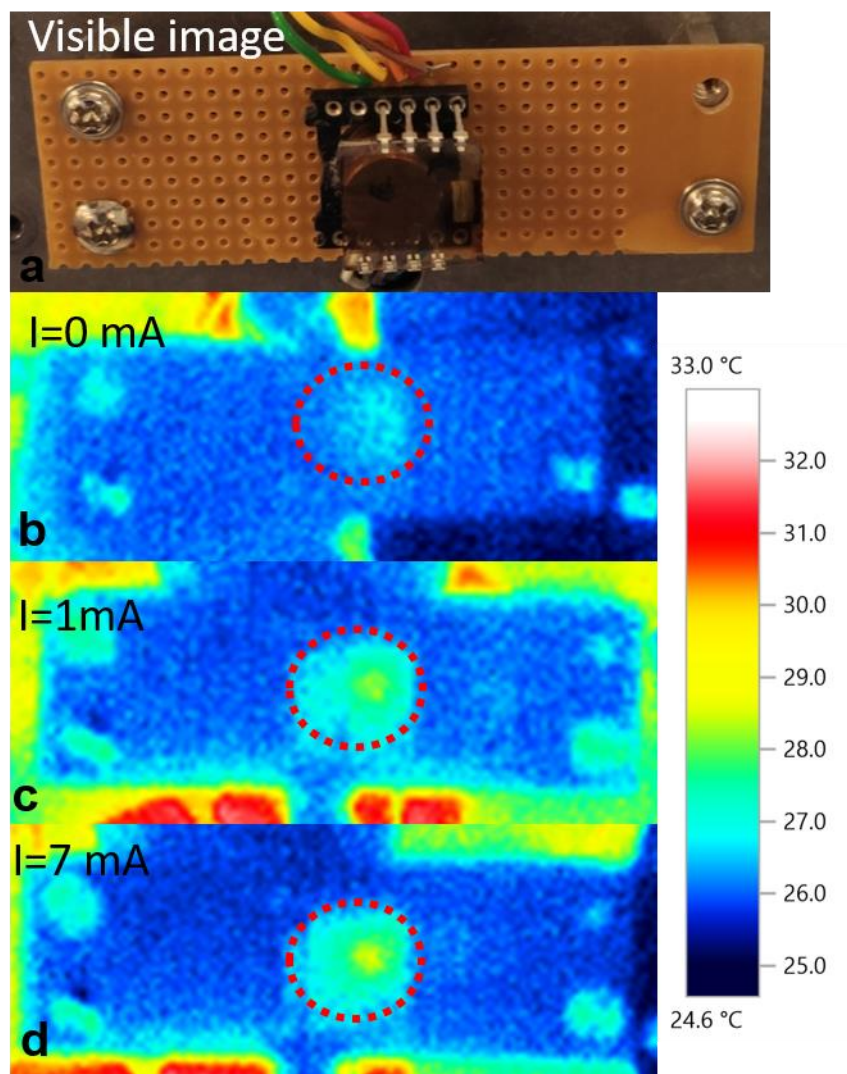
The relative performances of the LED, for 3 emission wavelengths, are given in Supplementary Figure 14. The EQE drops by a factor 2 when the wavelength peak is switched from 2 μm to 2.3 μm .



Supplementary Figure 14: Relative EQE as a function of applied current density for LEDs emitting at 2 μm , 2.15 μm and 2.3 μm . The 35 nm ITO substrates are used for all the devices here.

Supplementary note 8: temperature of the diode

To further determine the operating temperature of the diode, we have used a bolometer camera (testo 865) to measure the LED temperature under operation, see **Supplementary Figure 15a-d**.

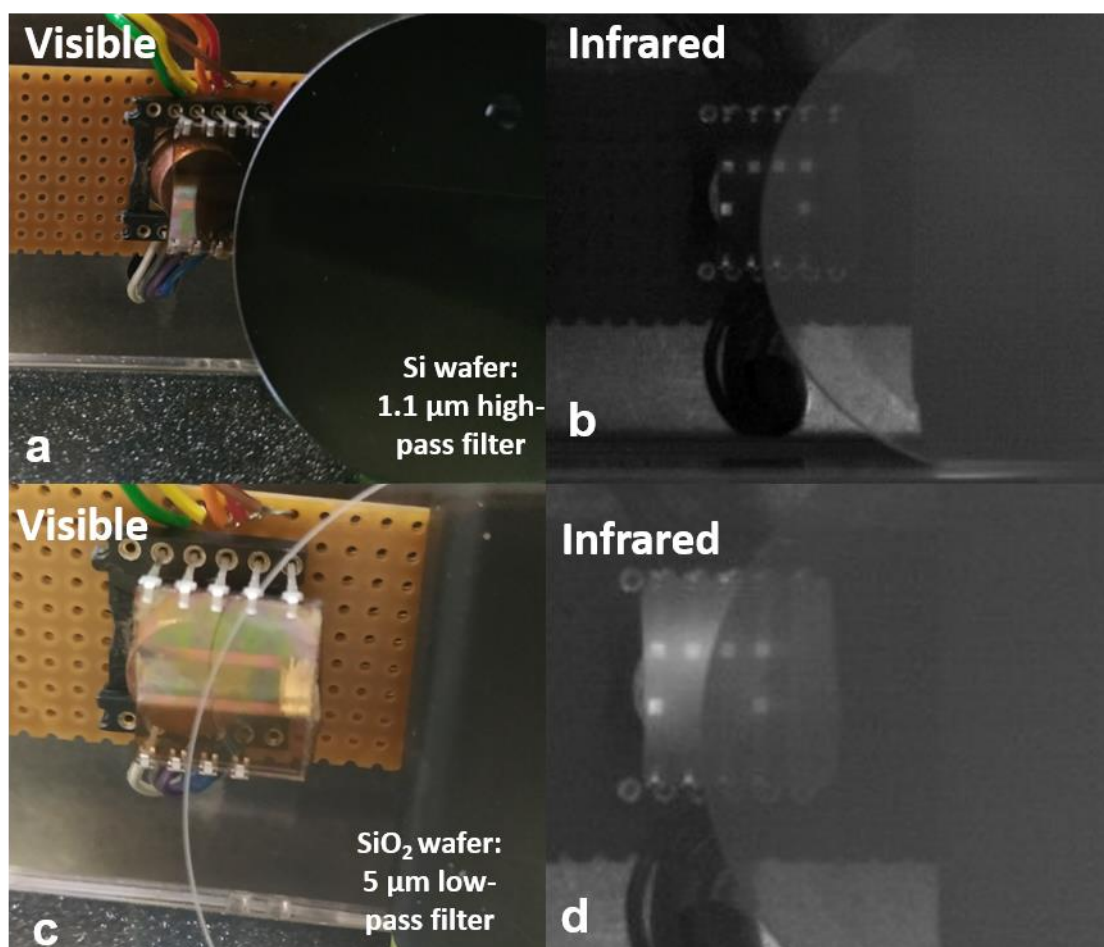


Supplementary Figure 15: Visible image of the LED (a) and infrared image (taken with a bolometer camera) of the LED under operation at 0 mA (b), 1 mA (c) and 7 mA (d) respectively.

We see that under operation there is a local heating effect. Temperature actually only rises by a few degrees. This measurement is a macroscopic measurement and is not able to give feedback on the local electronic temperature within the LED. However, the fact that EL (measured in device under operation) and PL (measured on solution) spectra mostly overlap suggest that *in-situ* temperature remains below the growth temperature of these nanoparticles (around 70 °C) otherwise sintering effect will be observed. And this would come with a spectral redshift.

Supplementary note 9: Spectral response of the LED

To further characterize the spectral emissivity of the LED, the operating LED (**Supplementary Figure 16a-b**) is visualized through a Si wafer which behaves as a high wavelength pass filter. The observation of the light spot through the wafer of Si confirms that emission occurs at longer wavelengths than the Si band-gap ($\approx 1.1 \mu\text{m}$). In consequence, the electroluminescence signal cannot be attributed of the PbS layer (emission around 1100 nm) used as hole injector. This claim is further supported by the direct measurement of the EL spectrum in the 1 to 2.5 μm range where only signal at 2 μm appears, see Figure 3a.

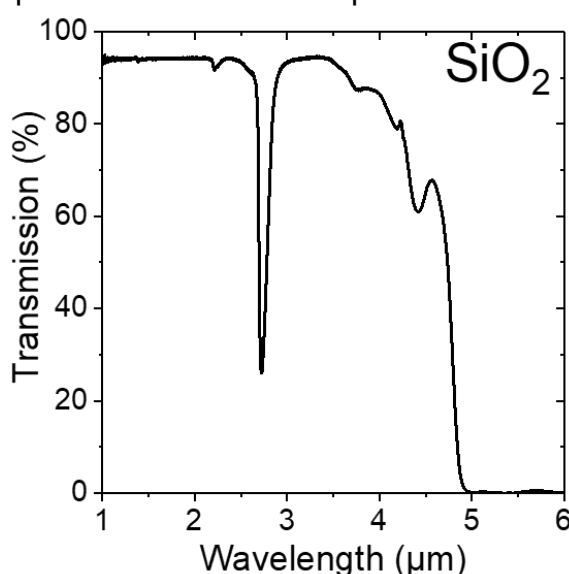


Supplementary Figure 16: Visible (a) and infrared (b) image of the LED under operation, while the LED is imaged through a double-side-polished undoped Si wafer ($\approx 1.1 \mu\text{m}$ high wavelength pass filter). Visible (c) and infrared (d) image of the LED under operation, while the LED is imaged through a double-side-polished silica wafer ($\approx 5 \mu\text{m}$ low wavelength pass filter).

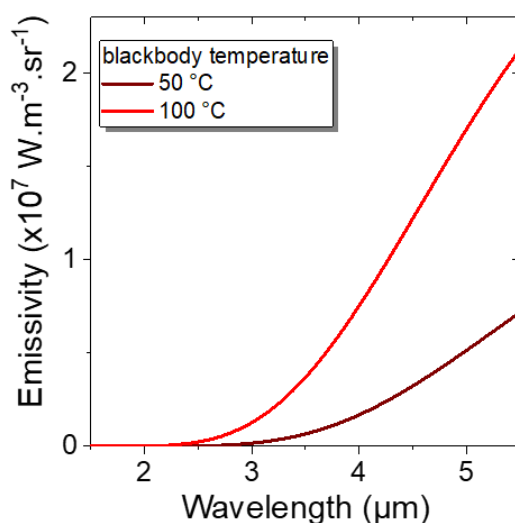
It is equally important to exclude, the possibility of an emission induced by a blackbody radiation resulting from Joule effect as current flows through the device. In this case, we

use a silica wafer (**Supplementary Figure 16c-d**), which acts as a low wavelength pass filter, with a cut-off at $\approx 5 \mu\text{m}$ (see **Supplementary Figure 17**).

LED effective temperature is typically in 50-100 °C range, see **Supplementary Figure 15**. We can exclude higher temperature since it will lead to particle sintering and in this case EL (conducted on device) and PL (on solution) will not match. For such temperature, the blackbody emissivity is provided in Supplementary Figure 18. Most of the emission ($\approx 50\%$ for 100 °C blackbody) occurs in the 4.8 μm to 5.5 μm range that is suppressed by silica filter. As a result, if light emission process was due to heating of the junction most of the light should be suppressed through the SiO_2 filter. This is not what is experimentally observed, see **Supplementary Figure 16d**. Again, the direct measurement of the EL spectrum (Figure 3b) reveals an emission peak much narrower than the blackbody emission corresponding to the temperature of the device operation.

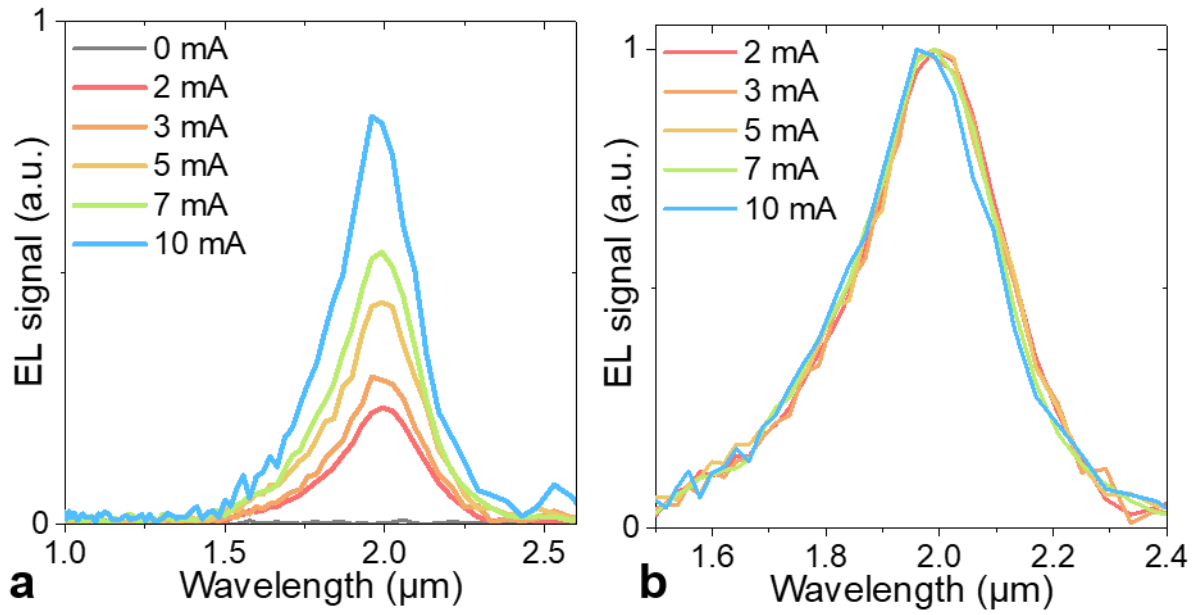


Supplementary Figure 17: Transmission of the SiO_2 glass used in figure 3.



Supplementary Figure 18: Emissivity of a blackbody at 50 °C and 100 °C in the spectral range of operation of the InSb camera.

A series of EL spectra have been acquired under different operating biases, see Supplementary Figure 19. We observe a small blueshift as the bias is increased. To understand this shift we can use the Kirchhoff's law that states that the spontaneous emission spectrum $I(\lambda)$ is proportional to the product of their absorption cross-section $A(\lambda)$ times Planck's law, which, in most cases of interest, can be simplified as: $I(\lambda) \propto A(\lambda) \cdot W(\lambda, T)$, where $W(\lambda, T) = 2hc^2\lambda^{-5} \exp[-hc/(\lambda k_B T)]$ is the Wien approximation of Planck's law, h and k_B are the Planck and Boltzmann constants and λ is the photon wavelength^{4,5}. As current is increased, the electronic temperature rises and the Boltzmann term blueshift



Supplementary Figure 19: EL (a) and normalized EL (b) spectra of the 2 μm emitting LED.

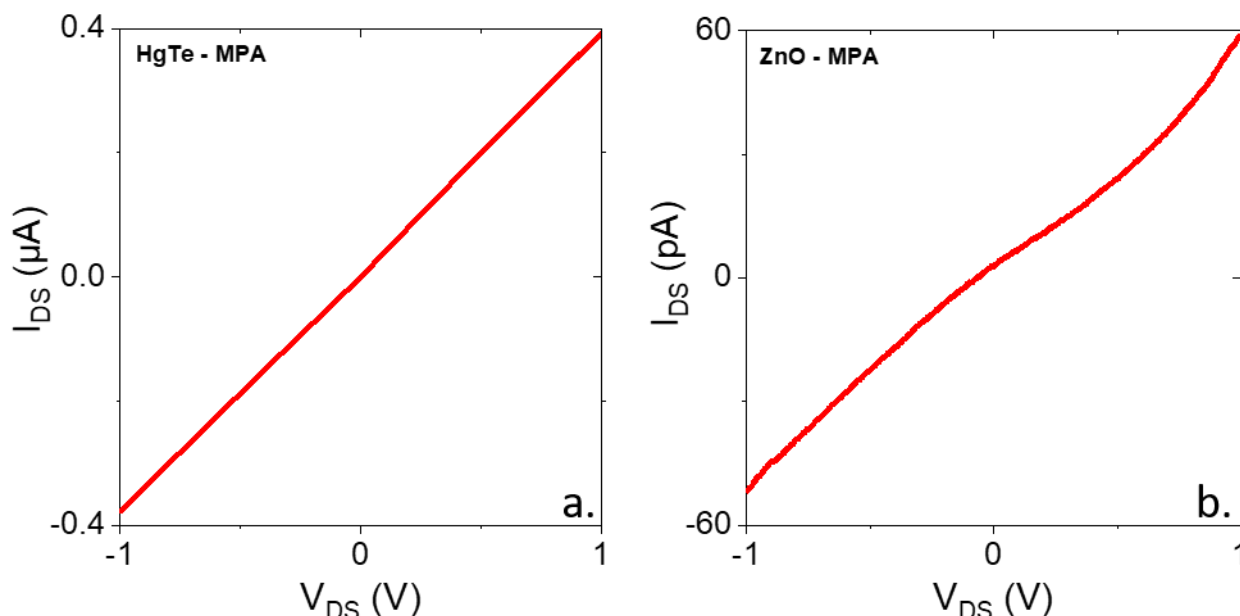
Supplementary note 10: State-of-the-art of SWIR emitters above 2 μm

Supplementary Table 2: Figures of merit for III-V light emitting diodes working in the 2-2.5 μm range. CW stands for continuous wave.

Active layer	Wavele ngth (μm)	Efficiency	Output power density	Test condition	Refere nce
InGaAsSb/GaSb	1.94	D(differential)QE =0.8%	/	5 μs pulse (2k Hz)	6
GaInAsSb solid solution	2.29	external photon yield =1.6%	42 mW/A	0.125 μs pulse (512 Hz)	7
Te-doped GaInAsSb solid solution	2.44	external photon yield =0.11%	4.3 mW/A	Quasi CW	7
GaInAsSb	2.53	/	/	/	8
Cascaded active regions of GaInAsSb	2.4	/	7.5 mW/A* cm^2	CW	9
MBE grown GaInSb/GaSb single QW	1.9-2.2	/	/	/	10
GaInAsSb	2.15	EQE=0.03%	/	/	11
GaInAsSb solid solutions (LED 22)	2.25	EQE=0.43%	1500 mW/A* cm^2	Quasi CW	12
InAs Quantum dash	1.97	EQE=0.94%	1200 mW/A* cm^2		13
GaInSb MQW (QJ403)	2.07	EQE=1.6 $\times 10^{-3}$ %	0.47 mW/A* cm^2	Quasi CW	13
InSb/GaSb QD stack (QH 326)	2.01	EQE=1.5 $\times 10^{-3}$ %	18000 mW/A* cm^2	Quasi CW	13
HgTe NCs	2 -2.3	EQE=0.28% at 2 μm	160 mW/A* cm^2	CW	THIS WORK

Supplementary note 11: Effect of the HgTe:ZnO content on the transport properties and electronic properties

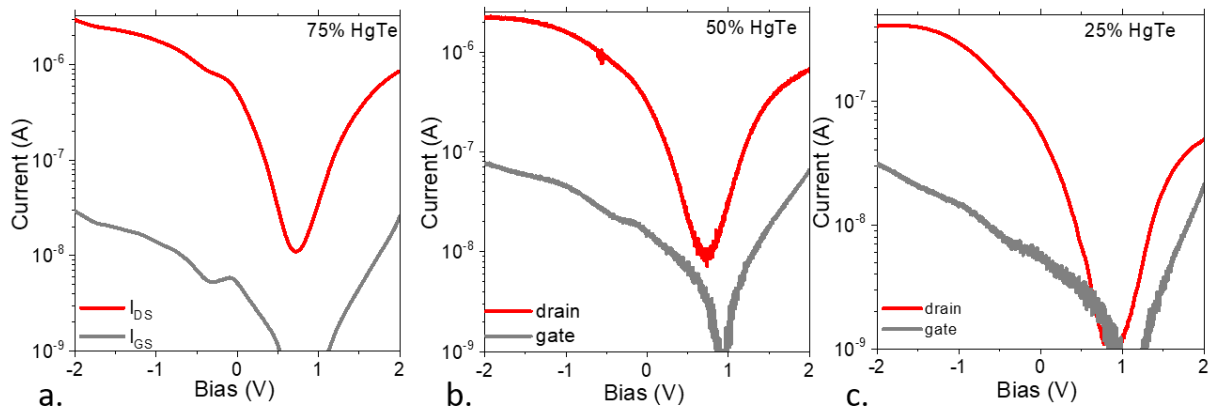
We have probed the transport properties of the material used in the emitting layer in a planar geometry using interdigitated electrodes. In this case, the IV curves are mostly ohmic, see Supplementary Figure 20.



Supplementary Figure 20: IV curves for a thin film of HgTe NCs (a) and for the ZnO NCs (b).

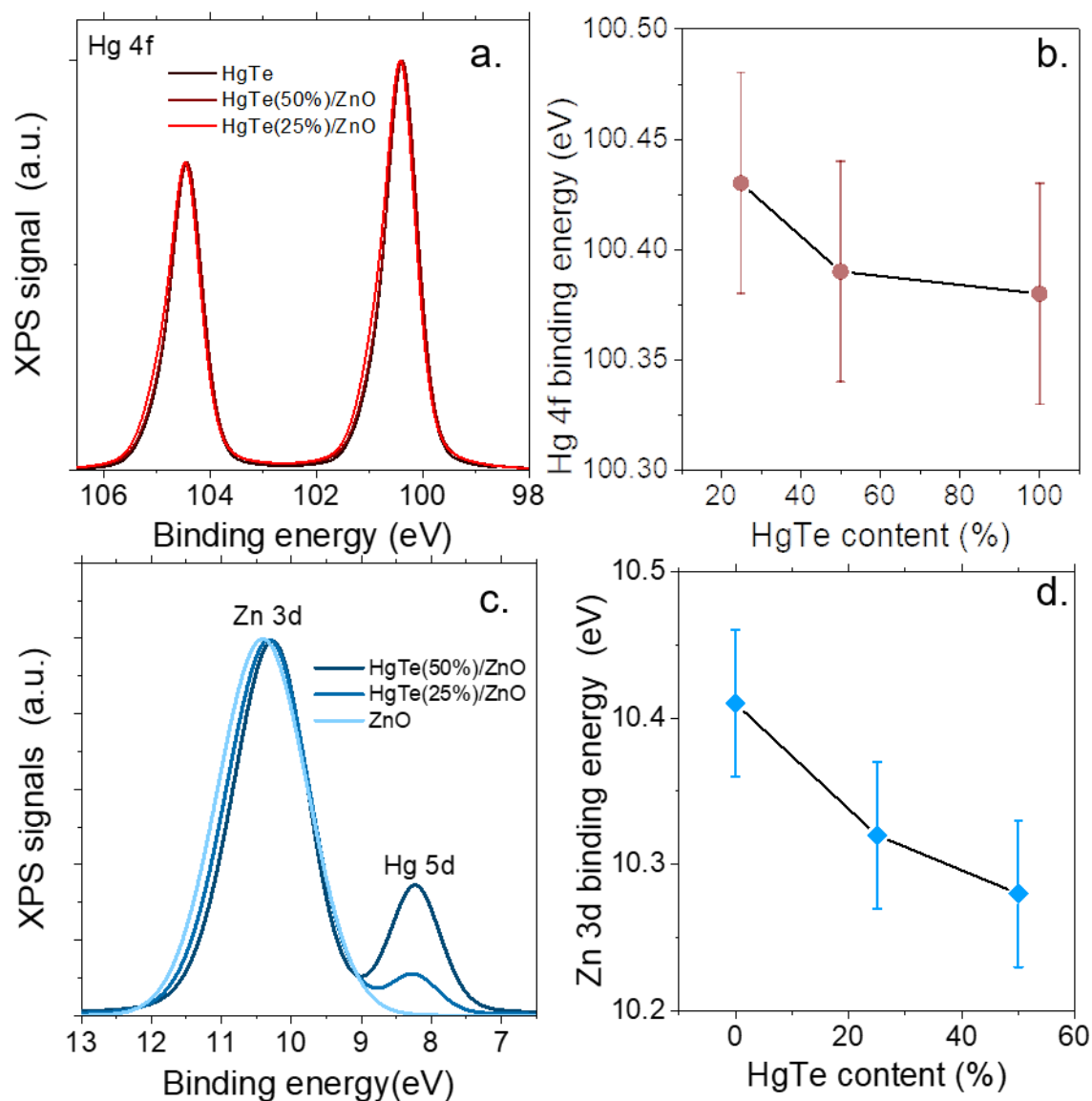
The transfer curves obtained for a field effect transistor (using electrolyte as gate) whose channel is made of a mixture of HgTe and ZnO NCs are given in Supplementary Figure 21. All curves preserve the ambipolar nature of HgTe NCs, with both rise of conduction under negative (hole injection) and positive (electron injection) gate bias. In the case of HgTe we have found the electron and hole mobilities to be respectively $5 \times 10^{-3} \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ and $3 \times 10^{-3} \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$, assuming a $1 \mu\text{F} \cdot \text{cm}^{-2}$ sheet capacitance for the gate electrolyte

ZnO presents a clear n-type conductance with a negative gate bias threshold (see figure 4b), that is not observed in any of the HgTe:ZnO mixture revealing that ZnO is not directly involved in charge conduction. To extract the gate bias at which the minimum of conductance occurs we always use the same sweep bias direction: from negative to positive gate bias.



Supplementary Figure 21: Transfer curves (drain and gate currents as a function of the applied gate bias) for a thin film of HgTe:ZnO with a HgTe content of 75 % (a), 50 % (b) and 25 % (c). V_{DS} is set at 0.5 V for all these measurements.

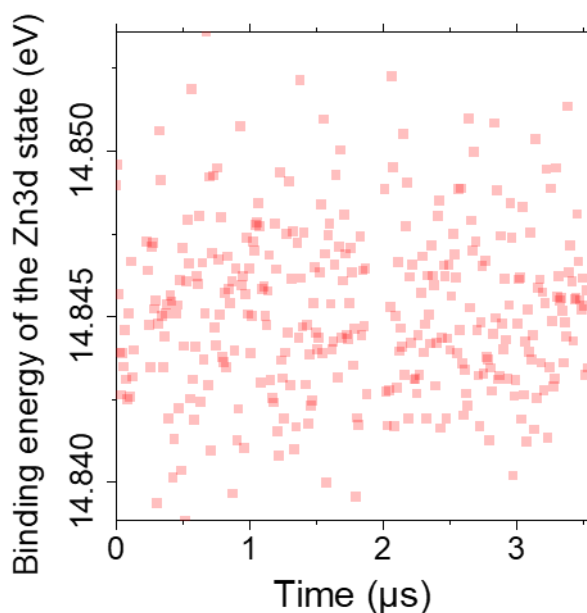
On the other hand, we observe a shift of Hg 4f and Zn 3d state with the HgTe/ZnO ratio. The binding energy of Hg 4f in the mixture is higher than the one from the pristine material, see Supplementary Figure 22a-b. The Zn 3d state binding energy is, at the opposite, reduced in the mixture compare to the raw ZnO. This can be interpreted as an electron transfer from HgTe to ZnO.



Supplementary Figure 22: X-ray photoemission spectra (a) and extracted binding energy (b) of Hg 4f for thin films of pure HgTe and HgTe:ZnO mixture with 25% and 50% volume ratio of HgTe. X-ray photoemission spectra (c) and extracted binding energy (d) of Zn 3d for thin films of pure ZnO and HgTe:ZnO mixture with 25% and 50% of HgTe. An error bar magnitude of 50 meV is estimated from calibration error (relative to Fermi level determination and determination of the photon energy) for part b and d.

Supplementary note 12: Time resolved photovoltage signal from ZnO film

As time resolved photoemission is performed on ZnO only, no light-induced shift is observed, see Supplementary Figure 23. In this experiment, a 800 nm (1.55 eV) laser is used as probe, which is below the ZnO band gap (> 3 eV). Due to sub band gap excitation, no light-effect is observed. On the other hand, in spite of the sub band gap excitation, a shift of the Zn 3d state is observed in the HgTe:ZnO mixture, highlighting the electrostatic coupling of the two materials (see figure 5 in the main text).



Supplementary Figure 23: Time dependence of the binding energy of the Zn 3d core level peak, after illumination by a short 800 nm laser pulse. The thin film is made of pure ZnO NCs.

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