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Supporting Information

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Explicit Gain Equations for Hybrid Graphene-Quantum-Dot Photodetectors

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(Supporting Information)

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Section 1 Raman Shift of graphene

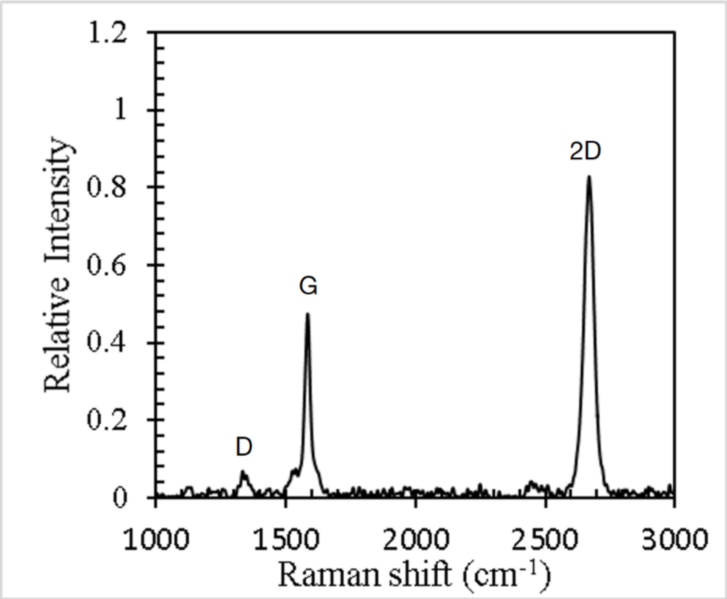


Fig.S1. Raman shift of graphene

Fig.S1 shows the Raman shift of purchased CVD- growth graphene. The 2D band located at 2673 cm^{-1} is observed to be a single symmetric peak with FWHM of 46 cm^{-1}, indicating the presence of single layer graphene. The result is further proved by the intensity ratio of the 2D to G band. The value of 1.75 is in agreement with previous literature reports.[1]

Section 2 Characterization of PbS QDs

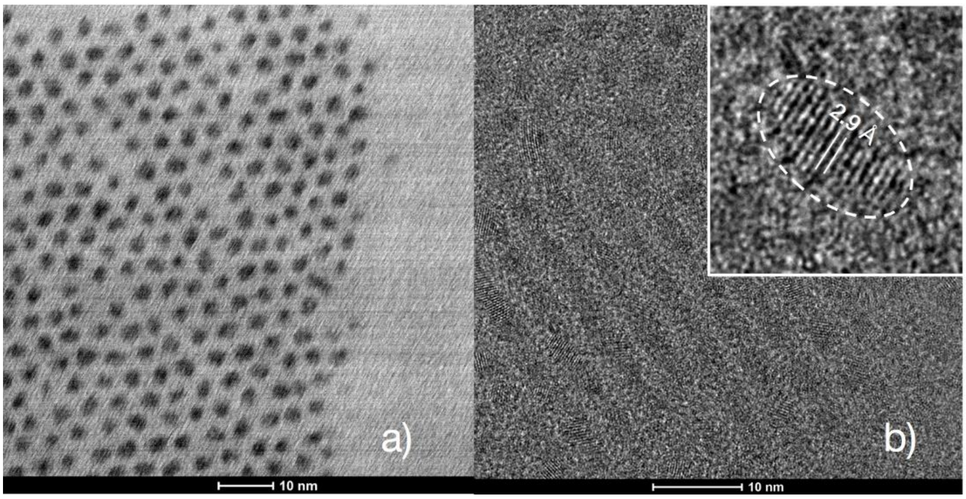


Fig.S2. a) TEM image and b) HRTEM image of PbS QDs, the inset shows a HRTEM of an individual PbS QD

Fig.S2 shows a TEM image of isolated PbS QDs on carbon coated TEM grid. The image demonstrates a narrow size distribution of PbS QDs with diameters mainly in range of 2 to 3 nm. The high-resolution TEM image shown in Fig.1b suggests that the

PbS QDs are highly crystalline, as indicated in the visible (200) lattice fringes with crystal plane spacing around 0.29 nm (inset image).

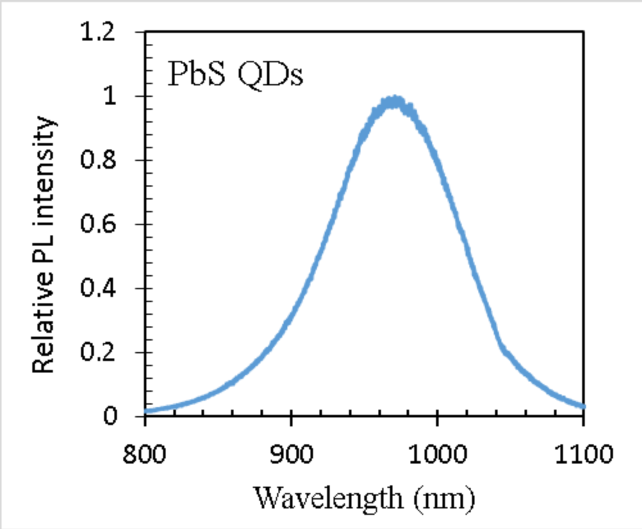


Fig.S3. PL emission spectra of PbS QDs

The corresponding photoluminescence (PL) emission peaks occur around 1.29 eV (960 nm), which is in good agreement with previous report.[2]

Section 3 Derivation of effective density of trap states

$$Q_{ss} = \int_0^{E_F}[D_{it}^{G-O}(E_F) + D_{it}^{G-Q}(E_F)]dE_F - qN_{eff}W_{dep}(V_{bi}) \qquad \text{eq(S1)}$$

$$W_{dep}(V_{bi}) = \sqrt{\frac{2\varepsilon V_{bi}}{qN_{eff}}} \qquad \text{eq(S2)}$$

$$D_{it} = \frac{dQ_{ss}}{dE_F} \qquad \text{eq(S3)}$$

By plugging eq(S1) and eq(S2) into eq(S3), we have

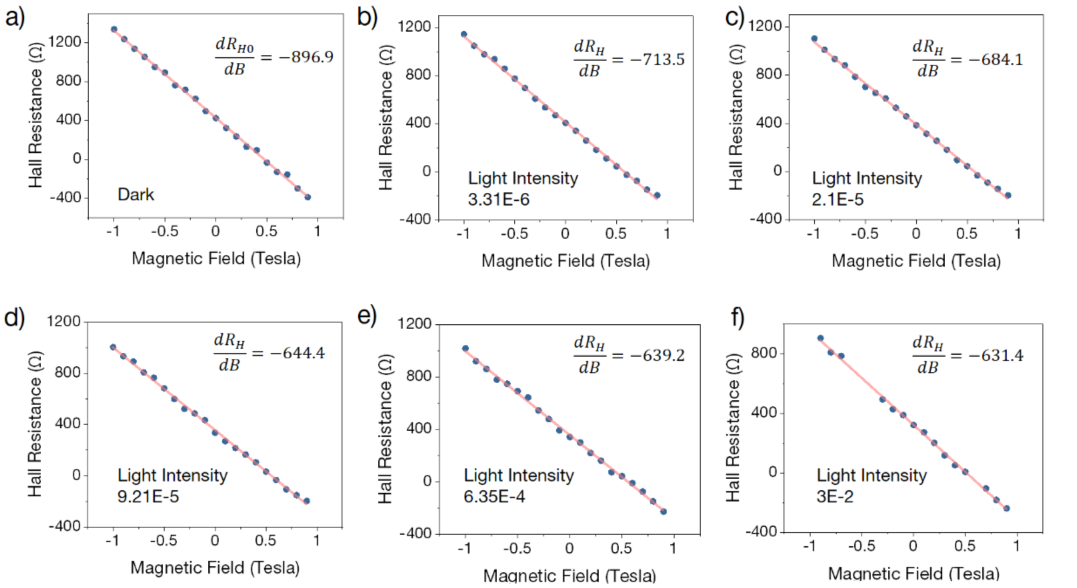
$$D_{it} = \frac{dQ_{ss}}{dE_F} = D_{it}^{G-O}(E_F) + D_{it}^{G-Q}(E_F) - qN_{eff}\frac{dW_{bi}}{dV_{bi}}\frac{dV_{bi}}{dE_F}$$

$$= D_{it}^{G-O}(E_F) + D_{it}^{G-Q}(E_F) - qN_{eff}\sqrt{\frac{2\varepsilon}{qN_{eff}}}\frac{1}{2\sqrt{V_{bi}}}\frac{dV_{bi}}{dE_F}$$

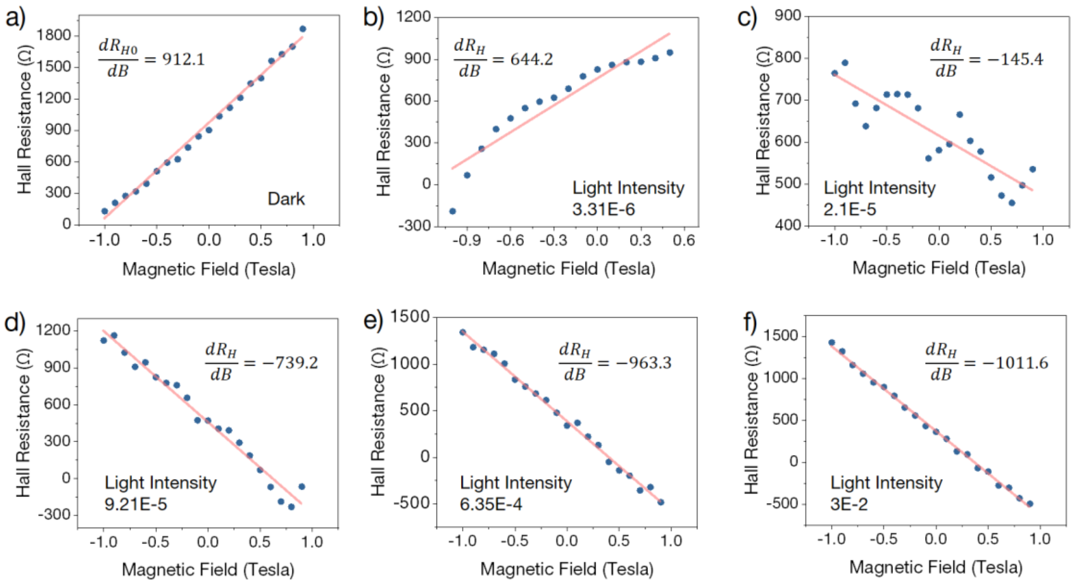
$$= D_{it}^{G-O}(E_F) + D_{it}^{G-Q}(E_F) - \frac{qN_{eff}W_{bi}}{2V_{bi}}\frac{dV_{bi}}{dE_F}$$

Section 4 Experimental data for photo Hall measurements

Vg=0 V



Vg=1.5 V



Section 5 Derivation of theoretical excess carrier concentration, photoconductance and photogain by using high order Taylor polynomials

Given $n = {n_i J_1(\frac{E_F}{kT})}\big/{J_1(0)}$, $p = {n_i J_1(-\frac{E_F}{kT})}\big/{J_1(0)}$, $\Delta E_F = kT \frac{\eta\omega(V_{bi})}{qv(E_F)} \ln\left(\frac{P_{light}}{P^s_{light}} + 1\right)$,

we can write the second order Taylor polynomials of ΔE_F.

$$\Delta n = \frac{n_i}{J_1(0)}\left[\frac{\ln(e^{E_F/kT}+1)}{kT}\right] kT \frac{\eta\omega(V_{bi})}{qv(E_F)} \ln\left(\frac{P_{light}}{P^s_{light}} + 1\right) + \frac{n_i}{2J_1(0)}\left[\frac{1}{(kT)^2}\frac{e^{E_F/kT}}{e^{E_F/kT}+1}\right]\left[kT \frac{\eta\omega(V_{bi})}{qv(E_F)} \ln\left(\frac{P_{light}}{P^s_{light}} + 1\right)\right]^2 \quad \text{eq.(S4)}$$

$$\Delta p = -\frac{n_i}{J_1(0)}\left[\frac{\ln(e^{-E_F/kT}+1)}{kT}\right] kT \frac{\eta\omega(V_{bi})}{qv(E_F)} \ln\left(\frac{P_{light}}{P^s_{light}} + 1\right) + \frac{n_i}{2J_1(0)}\left[\frac{1}{(kT)^2}\frac{e^{-E_F/kT}}{e^{-E_F/kT}+1}\right]\left[kT \frac{\eta\omega(V_{bi})}{qv(E_F)} \ln\left(\frac{P_{light}}{P^s_{light}} + 1\right)\right]^2 \quad \text{eq.(S5)}$$

$$\Delta\sigma = q\mu\frac{W}{L}(\Delta n + \Delta p)$$

$$= \frac{n_i\mu W}{J_1(0)L}\left[\frac{\eta\omega(V_{bi})}{v(E_F)}\frac{E_F}{kT} ln\left(\frac{P_{light}}{P^s_{light}} + 1\right) + \frac{1}{2q}\left(\frac{\eta\omega(V_{bi})}{v(E_F)}\right)^2\left(\ln\left(\frac{P_{light}}{P^s_{light}} + 1\right)\right)^2\right] \quad \text{eq.(S6)}$$

$$G = \frac{\frac{I_{ph}}{q}}{\frac{P_{light}A_{proj}}{\hbar\omega}} = \frac{\frac{\Delta\sigma V_{ds}}{q}}{\frac{P_{light}A_{proj}}{\hbar\omega}}$$

$$= G_{max}\frac{P^s_{light}}{P_{light}} ln\left(\frac{P_{light}}{P^s_{light}} + 1\right) + \frac{1}{2}\frac{\eta\omega(V_{bi})}{qv(E_F)}\frac{kT}{E_F}\frac{P_{light}}{P^s_{light}} G_{max}\left(\frac{P^s_{light}}{P_{light}}\ln\left(\frac{P_{light}}{P^s_{light}} + 1\right)\right)^2 \quad \text{eq.(S7)}$$

, in which $G_{max} = \frac{\hbar\omega n_i \mu V_{ds}}{P^s_{light} J_1(0) L^2}\frac{\eta\omega(V_{bi})}{qv(E_F)}\frac{E_F}{kT}$ with $\hbar\omega$ being the photon energy, n_i the electron concentration of intrinsic graphene, $P_{light}$the incident light intensity, μ the carrier mobility, V_{ds} the source-drain bias, $\frac{\eta\omega(V_{bi})}{qv(E_F)}$ is the photo gating efficiency, E_F the Fermi energy, kT the thermal energy at 300K, P^s_{light} the critical photocurrent (related to the depletion region width and minority carrier recombination lifetime), $J_1(0)$ the first order J function and L is the graphene device length.

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