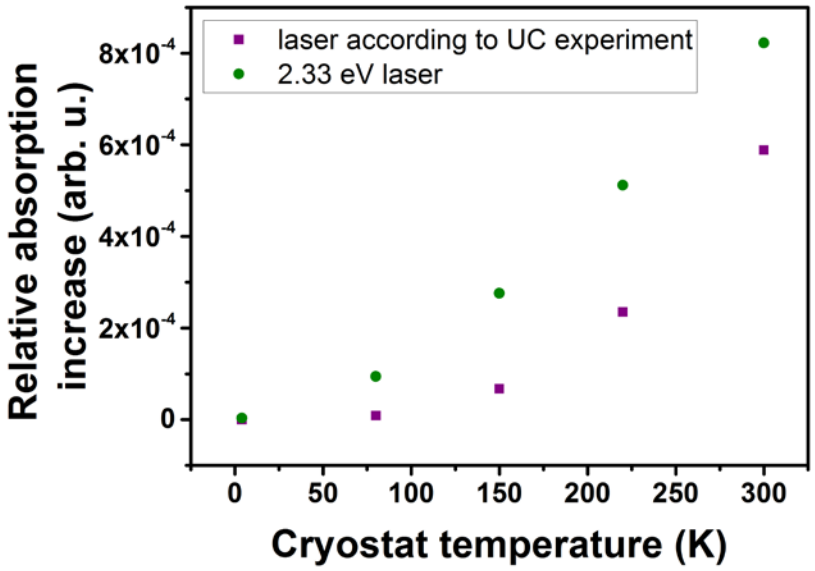
Supplementary Information

Photon upconversion in degenerately sulfur doped InP nanowires

Temperature dependent absorption

To estimate how the electron gas temperature influences the absorption we calculated the density of unoccupied states in the conduction band as a function of temperature. For the calculation the electron temperature was assumed to be equal to the measured cryostat temperature in Figure 3. Bulk InP values were used for the temperature dependence of the band gap and the electron mass and parabolic bands were assumed. The Fermi energy was estimated from the experimental data.



Calculated temperature dependence of the absorption of 2.33 eV photons (green circles) and of photons with energies according to the laser energies used in Figure 3 (purple squares). The absorption increase is calculated relative to the absorption at 4 K, however for the UC laser photon energies the calculated absorption at 4 K was zero.

For 2.33 eV photons the Fermi distribution is constant and the absorption depends purely on the density of available states. For laser energies below the Fermi energy the absorption depends strongly on the Fermi distribution and for 0.1 % unoccupied states the laser photon energy cannot be more than about 7kT below the Fermi energy. Thus for the experimental laser energy and Fermi energy a minimum electron temperature of about 86 K is required. For a fraction of 10^{-6} unoccupied states a temperature of at least 43 K is required. For a 4 K electron gas the absorption for the experimental energy values is virtually non-existing.

Fitting procedure

To calculate the electron gas temperature shown in figure 1 (b) the spectra in Figure 1 (a) were fitted using a parabolic density of states in the form

$$I_{DOS}(E) = \sqrt{\frac{E - E_g}{E_m - E_g}}$$

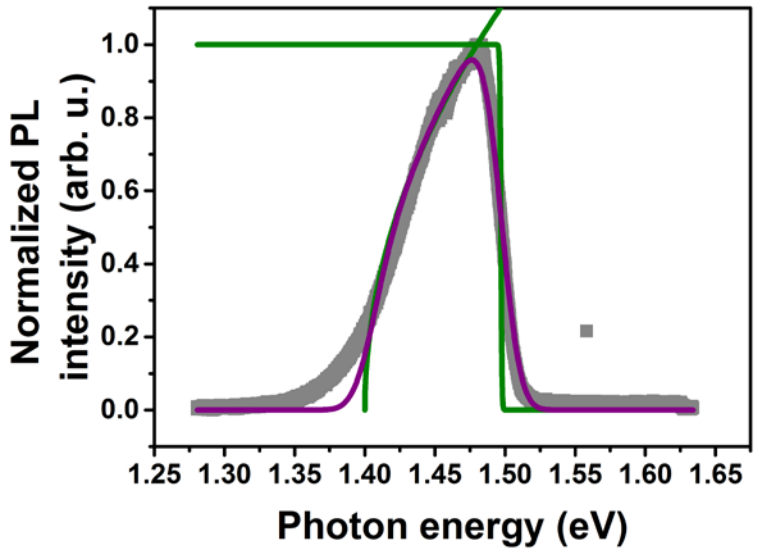
multiplied with a Fermi-Dirac distribution function

$$I_{fermi} = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}$$

where E is the energy variable and band gap energy E_g, scaling parameter E_m and temperature T are variable fitting parameters and k_B is the Boltzmann constant. The product of the equations above was then convoluted with a Gaussian peak in the form

$$I_g = h_g e^{-\frac{E^2}{2w^2}}$$

To reduce the number of variable fitting parameters the spectra were normalized and an off-set was subtracted before starting the fitting procedure. 4 K was used as lower limit for the temperature variable.



The best fit of the PL spectrum measured at 4 K with the lowest relative laser intensity (10^{-7}). The parabolic density of states and the Fermi-Dirac distribution are shown together with the resulting function after convolution. The displayed functions use the determined best fitting parameters. The width of the Gaussian convolution function was fitted for the lowest laser intensity and then kept fixed for the other laser intensity.