Quantum-Dot-Sensitized Solar Cell with Unprecedentedly High Photocurrent

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The reported photocurrent density (JSC) of PbS quantum dot (QD)-sensitized solar cell was less than 19 mA/cm² despite the capability to generate 38 mA/cm², which results from inefficient electron injection and fast charge recombination. Here, we report on a PbS:Hg QD-sensitized solar cell with an unprecedentedly high JSC of 30 mA/cm². By Hg⁺⁺ doping into PbS, JSC is almost doubled with improved stability. Femtosecond transient study confirms that the improved JSC is due to enhanced electron injection and suppressed charge recombination. EXAFS reveals that Pb-S bond is reinforced and structural disorder is reduced by interstitially incorporated Hg⁺⁺, which is responsible for the enhanced electron injection, suppressed recombination and stability. Thanks to the extremely high JSC, power conversion efficiency of 5.6% is demonstrated at one sun illumination.

Quantum dot (QD, semiconductor nanocrystal) has been recently drawing great attention as a material for solar energy conversion due to high absorption coefficient, tunable band gap and multiple exciton generation (MEG) effect1–4. QDs have been actively studied in dye-sensitized solar cell (DSSC) as alternatives to conventional organic dyes5. As a result, remarkable accomplishments have been achieved in recent years, where a power conversion efficiency (PCE) of ca. 5% was achieved using metal chalcogenides6,7 and around 10% using organic-inorganic perovskite8. However, most of the studied QDs for DSSC were based on the relatively large band gap materials (>1.5 eV)6–8. Using these materials, it may not be possible to utilize the full solar spectrum, which leads to a limited short-circuit photocurrent density (JSC) of ca. 20 mA/cm² (considering 20% loss from FTO glass)9. No successful examples have been reported on high JSC QD-sensitized solar cells based on low band gap QDs (<1.5 eV) although it has ability to generate extremely high JSC owing to near IR absorption.

Among the various low band gap QDs, PbS is one of the most intensively studied low band gap semiconductors since it has a high absorption coefficient of 1–5×10⁵ cm⁻¹ and wide range of tunable band gap owing to its large bohr exciton radius of 18 nm10,11. There have been a lot of efforts to use the PbS QD as a sensitizer. Antonio Braga et al. demonstrated a PCE of 2.21% with JSC of 10.91 mA/cm² using PbS/CdS QD photoelectrode being in contact with polysulfide electrolyte12. Very recently, it was enhanced to 3.82% with JSC of 18.84 mA/cm² by incorporating PbS/CdS QD in hierarchical porous TiO₂13. However, the observed JSCs are still far below the theoretical value of 38 mA/cm² (after considering 20% light reflection at FTO) when considering the band gap of ca. 1.0 eV.

Main drawback of PbS QD in QD-sensitized solar cell has been argued to be inefficient charge separation and collection due to slow electron transfer kinetics14. Electron injection from the conduction band of PbS QD to the conduction band of TiO₂ was measured to be a ca. 100 ns, which is five times slower than CdSe QD (20 ns from colloidal in organic solvent)14. In addition, it was also argued that PbS QD served as critical recombination center, which means that injected electrons in conduction band of TiO₂ tends to recombine readily with positively charged PbS QD, and thereby efficient charge collection was seriously impeded12,15. For efficient charge separation and collection from the PbS QD, injection and recombination kinetics of PbS QD must be tuned. However, little attempt has been made to date.

Here, we report on a QD-sensitized solar cell with JSC approaching 30 mA/cm² based on PbS:Hg QDs. Deposition of PbS:Hg QD on nanostructured TiO₂ is implemented by simple wet chemical process, where the photovoltaic performance is evaluated by using polysulfide as a redox electrolyte. Noticeable conversion efficiency of 5.6% with unprecedented high JSC is demonstrated under AM 1.5G one sun illumination. Electron injection and charge recombination kinetics are studied by femtosecond transient absorption measurements.
Chemical bonding nature surrounding Pb and Hg is investigated by extended X-ray absorption fine structure (EXAFS).

**Results**

Fig. 1a shows deposition process of PbS:Hg QD on nanostructured TiO₂ surface using successive ionic layer adsorption and reaction (SILAR) method. Pb²⁺ and Hg²⁺ ions are adsorbed on TiO₂ surface during the first dipping, which is followed by chemical reaction with S²⁻ ion in second bath to form PbS:Hg QD on TiO₂ surface. Concentration of HgCl₂ is varied from 0 mmol to 8 mmol to evaluate the effect of Hg²⁺ concentration. Fig. 1b shows TEM micrographs of bare TiO₂ and PbS:Hg QD-adsorbed TiO₂ with different HgCl₂ concentrations.

**Figure 1** Morphology and energetic properties of PbS and PbS:Hg QDs. (a) Deposition process of PbS:Hg QDs on mesoporous TiO₂ nanostructure using successive ionic layer adsorption and reaction (SILAR) method. (b) TEM micrograph of bare TiO₂ and QD coated TiO₂ nanoparticles using the cationic solution containing 0 mmol, 2 mmol, 4 mmol, 6 mmol and 8 mmol of HgCl₂. (c) Tauc plot calculated by using Kubelka-Munk equation from reflectance spectra. (d) UPS spectra of PbS:Hg QD adsorbed TiO₂ and extrapolation of low binding energy region. (e) Band edge alignment diagram for PbS and PbS:Hg QDs.
PbS:Hg QDs deposited on TiO₂ nanoparticles are compared in edge spectroscopy (XANES) spectra of bulk PbS and HgS with spite of the increased Hg²⁺ concentration (Supplementary Fig. S5 and S6 and Table S3). In case of 0 mmol HgCl₂, sparsely formed on the surface of TiO₂ nanoparticles regardless of using Kubelka-Munk equation 20 and Tauc plot 21 (Fig. 1c). The band gap of PbS:Hg QDs is determined by ultraviolet photoelectron spectroscopy (UPS) 22. Valence band maximum (VBM) is mainly dominated by S ion. The position of conduction band of PbS:Hg is hardly changed by Hg concentration, which indicates that VBM is hardly changed by Hg concentration, which will be discussed in detail based on previous research 12. However, degradation of J SC surprisingly is observed for the 6 mmol sample. This is considerably improved from 2.38% to 3.78%, which is mainly due to the decreased shunt resistance and series resistance are calculated from slope of J-V curves at short-circuit and at open-circuit region, respectively, using K2400 I-V system program based on LABVIEW (PV Measurements Inc) and plotted in Supplementary Fig. S9. Change in shunt resistance and series resistance are investigated as function of TiO₂ film thickness and number of coating cycle. Upon increasing TiO₂ film thickness or number of coating cycle, photocurrent is increased, while both shunt and series resistances are decreased. As can be seen in Tables S3 and S5, fill factors are decreased with increasing TiO₂ film thickness or number of coating cycle, which is due to the decreased shunt resistance despite the decreased series resistance.

EQE spectra are demonstrated in inset of Fig. 2b. Maximum EQE of PbS:Hg QD sensitized solar cell reaches 74.6% at 470 nm, which is improved by 78% compared to the maximum EQE of 41.8% at 400 nm for PbS QD sensitized one. EQE is substantially enhanced from visible to near IR region, where 123% at 500 nm (from 31.1% to 74%), 472% at 700 nm (from 9.41% to 53.8%) and 440% at 1000 nm (from 1.89% to 10.2%) are improved. Stability of the devices is evaluated by measuring J SC with respect to time after electrolyte injection (Fig. 2c). J SC of PbS QD sensitized solar cell sharply decreases immediately after electrolyte injection, where almost 80% of J SC degrades during the initial 180 seconds. Instability of PbS QD in polysulfide electrolyte is also observed in previous research 12. However, degradation of J SC surprisingly is overcome as the HgCl₂ concentration increases. Only 8% degradation of J SC is observed for the 6 mmol sample. This is considered to be attributed to change in chemical bonding nature of PbS owing to Hg²⁺ doping, which will be discussed in detail based on EXAFS analysis.

Femtosecond transient absorption (TA) spectra are measured to analyze the carrier dynamics in PbS:Hg QD-TiO₂ system along with pristine PbS QD-TiO₂ system. Fig. 2d shows femtosecond TA spectra in the near IR (NIR) region from 840 nm to 1200 nm, where the source of absorption is related to electrons in conduction band of TiO₂ 23,24. When considering the wavelength of pump light (490 nm) which is only absorbed by the QD, NIR absorption by electrons in TiO₂ conduction band can be ascribed to the injected photoelectrons from PbS and PbS:Hg QD to TiO₂. It can be noticed that AOD increases as the HgCl₂ concentration increases and is highest for HgCl₂ concentration of 6 mmol. Since AOD is related to the injected electrons, the higher AOD is indicative of more populated electrons in TiO₂ conduction band, which is responsible not only for higher J SC but also for higher Voc after doping of Hg²⁺ in PbS. It is
Figure 2 | Photovoltaic performance and femtosecond transient absorption spectra of PbS and PbS:Hg QDs. (a) Schematic device structure of QD-sensitized solar cell, (b) J-V curves and (c) Normalized $J_{sc}$ as a function of time for PbS:Hg QD-sensitized solar cells with different HgCl$_2$ concentration. Inset is EQE spectra for PbS and 14.6 at% Hg$_2^+$ (6 mmol) doped PbS. (d) Transient absorption spectra at 0.5 ps delay. The wavelength of pump light was 490 nm. (e) Transient absorption time profile and (f) Normalized AOD at 2 ($\pm$ 0.1) ps (red), 20 ($\pm$ 1) ps (blue), and 300 ($\pm$ 15) ps (black) with standard deviation. The wavelength of probe was 870 nm. (g) Intensity averaged decay time constants (blue) and rise time constants (red) with error bars.
expected that increase in ΔO.D. leads to upward shift of Fermi level, resulting in increase in \(V_{OC}\). The observed ΔO.D. is well correlated with change in \(V_{OC}\) measured in Table S4, where \(V_{OC}\) increases from 0.387 V to 0.426 V as the HgCl\(_2\) increases from 0 mmol to 6 mmol and slightly decreases to 0.424 with 8 mmol. Decreased ΔO.D. for 8 mmol HgCl\(_2\) condition might be related to blue shift of absorption caused by the increased band gap. TA time profile in this region exhibits triply exponential decays with an ultrafast rising component as a result of numerical convolutions with cross-correlation function (FWHM = 200 fs). In order to compare the carrier dynamics, ΔO.D. is normalized as a function of time (Fig. 2c). The decay dynamics slow down monotonically with an increased concentration of HgCl\(_2\) from 0 mmol to 8 mmol. In Fig. 2f, ΔO.D. at arbitrary time delays of 2 ps, 20 ps, and 300 ps are elucidated with different HgCl\(_2\) concentration. The ΔO.D. at arbitrary time increases with increased HgCl\(_2\) concentration, which have the same trend with the shorter time delay (−1 ps−13 ps). Numerically fitted parameters for decay time profile are listed in Table S6 where triply exponential model (eq 1) is used, and average decay time constants (\(\tau_d\)) are estimated by eq 2,

\[
F(t) = A_1e^{-t/\tau_1} + A_2e^{-t/\tau_2} + A_3e^{-t/\tau_3}
\]

\[
\tau_d = \frac{\sum_{i=1}^{3} \tau_i^{2} A_i^{2}}{\sum_{i=1}^{3} A_i \tau_i}
\]

Where \(A_i\) and \(\tau_i\) are triply exponential decay components constant. Average decay time constant increases from 151 ps to 186 ps as the HgCl\(_2\) concentration increases from 0 mmol to 8 mmol (Fig. 2g). Absorption decay dynamics of electrons in conduction band of TiO\(_2\) result from recombination of injected electrons with holes in QDs in absence of electrolyte. Therefore it is obvious that charge recombination in TiO\(_2\) is substantially suppressed as the HgCl\(_2\) concentration increases, which is responsible for the increased \(V_{OC}\). Also, considering that charge collecting efficiency is inversely proportional to recombination kinetics, suppressed charge recombination may lead to improvement of charge collecting efficiency (\(\Phi_{col}\)). Ultrafast rising of ΔO.D. for Hg\(^{2+}\) doping provides a faster electron injection in PbS:Hg QD than in PbS QD\(^{39}\). Therefore, it is possible to estimate the electron injection kinetics by measuring the time for ΔO.D. signal to reach its maximum. Fitted rise time constants are listed in Table S6 and Fig. 2g. Rise time constant decreases from 340 fs to 270 fs as the HgCl\(_2\) concentration increases from 0 mmol to 8 mmol, which implies an improved electron injection efficiency (\(\Phi_{inj}\))\(^{29}\). It may not be ruled out that upward shift of PbS QD conduction band upon Hg\(^{2+}\) doping provides a driving force for faster electron injection in PbS:Hg QD than in PbS QD\(^{39}\). However, since the band shift of CBM of QDs seems favoring electron injection toward TiO\(_2\), one hypothesis for the improved functional properties of the cell and the mechanism for the inhibition of charge recombination seems to be related to structural reinforcement by Hg doping.

The effect of Hg\(^{2+}\) doping on the local structure of Pb\(^{2+}\) ions in the PbS:Hg QD adsorbed on TiO\(_2\) surface is investigated with EXAFS analysis at Pb and Hg L\(_3\)-edge. As can be seen in Fig. 3a, regardless of Hg doping, all the present PbS:Hg QDs adsorbed on TiO\(_2\) show typical EXAFS oscillation of the reference PbS, confirming the formation of rocksalt-structured PbS phase. A closer inspection on the experimental spectra reveals that the wavelength of EXAFS oscillation becomes greater with the increase of Hg content, strongly suggesting the shortening of (Pb-S) bonds upon Hg doping\(^{34}\). The decrease of (Pb-S) bond distance upon the Hg doping is obviously verified by the quantitative EXAFS fitting analysis showing the gradual decrease of (Pb-S) distance with the increase of HgCl\(_2\) concentration (Fig. 3c, Fig. 3e and Table 1). This result provides strong evidence for the reinforcement of the (Pb-S) bonds by the doping of Hg\(^{2+}\) ions. In addition to the systematic variation of bond distance, there is an overall decreasing trend of Debye-Waller factor (σ\(^2\)) with the increase of HgCl\(_2\) concentration, indicating the depression of structural disorder around Pb ions (Table 1)\(^{31}\). Such a decrease of structural disorder is also attributable to the reinforcement of (Pb-S) bonds upon the Hg doping. The strengthening of chemical bonds between Pb and S leads not only to the increase of the optical band gap of PbS QD but also to the upward shift of the conduction band of PbS with antibonding character. For local structure of mercury ion, detailed analysis on the Hg L\(_3\)-edge EXAFS spectra (Fig. 3b, 3d and 3f) is performed as follows. Since the value of coordination number obtained from the EXAFS fitting analysis corresponds to the product of coordination number (CN) and amplitude reduction factor (S\(_0\))\(^{3}\), it is necessary to get the knowledge of amplitude reduction factor for a Hg-S pair, prior to determining the exact coordination number of Hg ion. In the present analysis, the S\(_0\) value obtained from the pure HgS reference is used to calculate the exact CN of mercury in the present PbS:Hg QDs. As listed in Table 1, this fitting analysis yields the CN of ~3.7–4 for mercury ions in the PbS:Hg QDs, strongly suggesting the stabilization of Hg ions in the interstitial tetrahedral sites. The tetrahedral symmetry of Hg ions in the PbS:Hg QDs is further confirmed by the comparison of their bond distance with that of pure (bulk) HgS material. In comparison with the reference HgS where the Hg ions are stabilized in the tetrahedral sites with the (Hg-S) bond distance of 2.49 Å, the present PbS:Hg QDs show a shorter bond distance of ~2.36–2.38 Å. Since the decrease of CN shortens the bond distance, the shorter (Hg-S) bond distance of the PbS:Hg QDs than that of the pure HgS underscores that the CN of Hg ion is smaller than or similar to four (i.e. the CN of Hg in the reference HgS). This result provides strong evidence for the stabilization of mercury ions in interstitial tetrahedral sites. If the Hg ions exist in octahedral symmetry (Pb site) with CN = 6, the PbS:Hg QDs should show a longer (Hg-S) bond distance than that of the reference HgS (2.49 Å) with CN = 4. The tetrahedrally coordinated interstitial Hg\(^{2+}\) ions contribute to contraction of lattice and consequently causing a reinforcement of Pb-S bond (Fig. 3g). Theoretically calculated (Hg-S) bond distance for 6 mmol HgCl\(_2\) case is 2.386 Å, which is well consistent with the observed bond distance of 2.369 Å. Both the enhancement of (Pb-S) bond strength and the improvement of structural ordering around Pb\(^{2+}\) ions strongly suggest the enhanced structural stability of PbS QD via the Hg doping. In addition, the enhanced structural ordering is likely to lead to reduction of deep trap density\(^{23,29}\), which contributes to suppression of charge recombination. Thus, the structural reinforcement by Hg addition is playing major role in improving the functional properties of the cell, and is the main mechanism for the inhibition of charge recombination compared to the role of band shift.

Best performance of PbS:Hg QD sensitized solar cell in this study is obtained by combination of 6 mmol HgCl\(_2\) condition, scattering layer and CsOH additive in electrolyte. Additon of 0.3 M CsOH into the electrolyte improves fill factor of the device by 13% (Supplementary Fig. S10 and Table S7), which is probably due to decrease in interfacial resistance at electrolyte/Cu\(_2\)S counter electrode\(^{34}\). Light scattering layer increases further EQE at longer wavelength (EQE of 56% at 800 nm and 32% at 1000 nm). As a result, \(J_{SC}\) reaches 29.98 mA/cm\(^2\), leading to a PCE as high as 5.58% at AM 1.5G one sun illumination (Fig. 4).

**Discussion**

We presented a mercury doped PbS QD-sensitized solar cell with extremely high \(J_{SC}\) of 30 mA/cm\(^2\). Such a high \(J_{SC}\) was realized by reinforcing Pb-S bond via incorporation of Hg\(^{2+}\) ion into the interstitial site of PbS lattice. The improved ordering and covalency surrounding Pb ion led to faster electron injection and suppressed charge recombination. It is therefore concluded that structural...
reinforcement by Hg addition plays a major role in improving the functional properties of the cell, and is the main mechanism for the inhibition of charge recombination. Based on our findings, optoelectronic and photovoltaic properties of QD materials are expected to be significantly improved by careful investigation on chemical bonding nature. Furthermore, such a preponderant enhancement in QD photovoltaic materials is believed to provide new insight into super high efficiency solar cell technology such as third generation MEG photovoltaics.

**Methods**

Sensitization of PbS:Hg QD on mesoporous TiO$_2$ layer. TiO$_2$ nanoparticles and films were prepared according to the method described elsewhere$^{35}$. Fluorine-doped tin oxide (FTO) glass (Pilkington, TEC-8, 8 V/sq) was cleaned with ethanol using ultrasonic cleaner for 15 min and subsequently UV/Ozone cleaning was conducted for 15 min to remove organic contaminants. A dense blocking layer was prepared on the cleaned FTO glass using 0.1 M Ti(IV) bis (ethyl acetoacetato) diisopropoxide (Aldrich, 98%) in 1-butanol (Aldrich, 99.8%) solution. TiO$_2$ paste was prepared by mixing the synthesized nanocrystalline TiO$_2$, terpineol (Aldrich, 99.5%), ethyl cellulose (Aldrich, 46 cp) and lauric acid (Fluka).
using three-roll-mill for 40 min to disperse nanoparticles sufficiently. The TiO$_2$ paste was coated on the blocking layer coated FTO substrate using doctor-blade method and annealed at 550 °C for 1 h in air. Thickness of the annealed mesoporous TiO$_2$ layers was measured by an alpha-step IQ surface profiler (KLA Tencor). Successive ionic layer adsorption and reaction (SILAR) method was used to sensitize the TiO$_2$ nanoparticles with PbS:Hg QDs as described in Fig. 1a. Briefly, mesoporous TiO$_2$ coated electrode was first dipped in aqueous solution of 0.1 M Pb(NO$_3$)$_2$ (Aldrich, 99.99%) for 1 min, followed by dipped in 0.1 M Na$_2$S$_2$ (Aldrich) for 1 min. Between each dipping, the electrode was thoroughly washed with DI (deionized) water. For PbS:Hg, 2–8 mmol of HgCl$_2$ (Sigma-Aldrich, 99.5%) was added to cationic precursor solution. These processes were defined as one cycle and several coating cycle was repeated to obtain the optimum photovoltaic performance in each condition (2 cycles for 0 mmol, 4 cycles for 2 mmol and 4 mmol and 6 cycles for 6 mmol and 8 mmol) (Supplementary Fig. S5, Fig. S6 and Table S3). To enhance the photovoltaic performance, ZnS passivation layer was deposited after PbS:Hg deposition on TiO$_2$ by using aqueous solution of 0.1 M Zn(CH$_3$COO)$_2$ (Aldrich, 99.99%) and 0.1 M Na$_2$S$_2$.

**Table 1**: Results of non-linear least-squares curve fitting analysis for the Pb and Hg L$_3$ edge spectra of the PbS and PbS:Hg QDs adsorbed on TiO$_2$ with different HgCl$_2$ concentrations. Bulk PbS and HgS are references. CN, R and $\sigma^2$ represent coordination number, interatomic distance and Debye-Waller factor.

| Bond          | CN | R (Å) | $\sigma^2$ (10$^{-6}$ Å$^2$) |
|---------------|----|-------|-----------------------------|
| Bulk PbS      |    |       |                             |
| 0 mmol PbS    | 6  | 2.869 | 17.58                       |
| 2 mmol PbS    | 3.07 | 2.796 | 26.30                       |
| 4 mmol PbS    | 2.95 | 2.780 | 18.77                       |
| 6 mmol PbS    | 3.16 | 2.772 | 20.88                       |
| 8 mmol PbS    | 1.94 | 2.755 | 15.88                       |
| Bulk HgS      |    |       |                             |
| 2 mmol HgS    | 4.05 | 2.359 | 6.78                        |
| 6 mmol HgS    | 3.73 | 2.369 | 5.15                        |
| 8 mmol HgS    | 3.96 | 2.373 | 6.33                        |

**Figure 4**: Photovoltaic performance of PbS:Hg QD-sensitized solar cell. J-V curve and EQE spectrum (inset) of PbS:Hg QD-sensitized solar cell. HgCl$_2$ concentration was 6 mmol and number of coating cycle was 6. Total TiO$_2$ film thickness was 25 μm, comprising 5 μm with 20 nm TiO$_2$ particles and 20 μm with 40 nm and 500 nm TiO$_2$ particles.

PbS:Hg film. Both of the deposition was performed for 10 min at room temperature, which led to 300 nm thick-PbS and 235 nm thick-PbS:Hg on glass substrate. Hall voltage was measured under bias current of 1 μA for PbS film and 3 μA for PbS:Hg film and applied field was adjusted from 1 to 5 kG using LaKeshore 7500 series Hall Measurement System at room temperature. Resistivity, type of conductivity, sheet carrier density, and mobility of majority carrier were calculated by van der Paw method.

**Femtosecond transient absorption measurement**: Pump-probe transient absorption (TA) experiments were carried out using commercial Helios system (Ultralast Systems). The pump beam of 490 nm with a pulse energy of 1.6 mJ was obtained from an optical parametric amplifier (Light conversion, TOPAS-C), pumped by a regeneratively amplified Ti:Sapphire laser system (Coherent, Libra) with 1-kHz repetition rate. The probe pulse was a white light continuum generated by focusing a small portion of the amplifier output through a c-axis sapphire window.

**XANES and EXAFS measurements**: Local structure of QD was analyzed by XANES (X-ray absorption near edge structure) and EXAFS (extended X-ray absorption fine structure). The Pb L$_3$-edge XANES/EXAFS data were collected at room temperature in a fluorescent mode at the beam line 10C at the Pohang Accelerator Laboratory (PAL), Korea. The spectra were calibrated by measuring the spectrum of Pb foil simultaneously. Data analysis for the experimental spectra was performed with the standard procedure by using UWXAFS 2.0 program. For the fitting of the reference, the amplitude reduction factor (S$_0^2$) was varied while the CN was fixed to the crystallographic value. All the bond distances (R), interatomic distance (s), Debye-Waller factor (σ$^2$), and energy shifts ($E$) were allowed to vary. In order to exactly estimate the CNs of lead ions in the present PbS:Hg QDs adsorbed on TiO$_2$, S$_0^2$ was fixed to the value from the reference PbS.

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Author contributions
N.-G.P. contributed to the conception and design of the experiment, analysis of the data and writing the manuscript with assistance of J.-W.L. J.-W.L. carried out design and synthesis of QDs materials, preparation of the devices, device performance measurements. D.-Y.S. synthesized TiO2 nanoparticles with different particle size. T.K.A. and H.-W.S. contributed to the femto-second data analysis. S.S. and H.H. carried out femtosecond transient measurements. M.I.K. collected UPS data. I.Y.K. and S.-H.J. measured the extended x-ray absorption fine structure (EXAFS) at PAL and analyzed the EXZFS data.

Additional information
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