Simultaneously Enhancing Dissociation and Suppressing Recombination in Perovskite Solar Cells

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Abstract

This article reports the experimental studies on simultaneously enhancing the dissociation and suppressing the recombination in perovskite solar cells by using high-dielectric Nickel Oxide (NiOx) as hole transport layer. Specifically, the magneto-photocurrent, generated by the electron-hole pairs, surprisingly becomes negligible at short-circuit condition when the NiOx is used to replace the poly (3,4-ethylenedioxythiophene) poly (styrene-sulfonate) (PEDOT:PSS). This indicates that the NiOx transport layer leads to a complete dissociation of electron-hole pairs in perovskite layer. On the other hand, the negligible magneto-photocurrent can be recovered to become appreciable when a forward bias is applied towards open-circuit condition to weaken the built-in field. This magneto-photocurrent result suggests that the NiOx transport layer enhances the built-in field, completely dissociating the electron-hole pairs. Furthermore, the photoinduced capacitance studies confirm that the built-in field is enhanced essentially through static and dynamic parameters, by removing the interfacial traps and decreasing the accumulation of photogenerated carriers. The time-resolved photoluminescence shows that the NiOx/CH₃NH₃PbI₃ interface leads to a reduction on non-radiative recombination, increasing the fraction of useful excitons available for photovoltaic actions. Moreover, the field-dependent photoluminescence measured alternatively at short-circuit and open-circuit conditions shows that the NiOx layer can also suppress the radiative recombination within available excitons, boosting the photovoltaic actions. Therefore, our studies reveal that the high-dielectric NiOx transport layer can simultaneously enhance the dissociation of electron-hole pairs and suppress both non-radiative/radiative recombination, leading to the more efficient generation of J_{sc} and V_{oc} in perovskite solar cells.

Keywords: Perovskite solar cells; Dissociation; Non-radiative/radiative recombination; Interfacial traps; Dielectric effects

1. Introduction

Organo-metal halide perovskites have achieved a remarkable progress in the photovoltaic community with the certified efficiency of 22.1% in less than five years[1,2]. This rapid progress can be attributed to two major improvements. First, charge recombination has been dramatically suppressed, particularly through the non-radiative channel, by improving perovskite film quality through defect engineering [3-6]. Second, charge collection and extraction at electrode interface have been significantly improved through interface engineering by selecting ideal transport layer with high charge selectivity and appropriate energy level alignment[7-10]. Recent studies have demonstrated that the transport layer plays a major role in controlling transient photocurrent/photovoltage response and current-voltage (I-V) hysteresis phenomenon in perovskite solar cells (PSCs) [11,12]. Such I-V hysteresis phenomenon has been commonly shown in the n-i-p devices with TiO_x and Spiro-OMeTAD as transport layers, which could due to serious interaction with the mobile ions, such as iodine ions/interstitials, modifying the interface barriers as well as bulk self-degradation[11,13]. However, introducing the PCBM as either transport interlayer or bulk dopants in perovskites are shown to suppress I-V hysteresis phenomenon due to the passivation effect of grain boundary defects[14-16]. Therefore, the inverted p-i-n perovskite solar cells with PEDOT:PSS and PCBM transport layers usually exhibit less I-V hysteresis [12,17]. However, the inverted perovskite solar cells usually suffer from a significant loss in the open-circuit voltage (V_{oc}), thereby limiting the photovoltaic efficiencies. Recently, the high-dielectric Nickel Oxide (NiO_x) ($\epsilon_r = 15$ at 1 kHz and 298 K, refractive index $n = 1.8\sim 2.3$ in visible light regime)[18,19] has been successfully used to replace low-dielectric PEDOT:PSS (refractive index $n = 1.47\sim 1.58$)[20] as the hole transport layer (HTL) in the inverted perovskite solar cells, which demonstrate substantial improvement on the photovoltaic performance [21-24]. This improvement has been attributed to the improved

energy-level alignment due to the lower HOMO (-5.4 eV) of NiOx as compared to the PEDOT:PSS with the higher HOMO (-5.0~-5.2 eV)[22,25]. However, it has been found that the NiOx exhibits weaker quenching effect on the photoluminescence (PL) of perovskite layer as compared to PEDOT:PSS [22,26], which seems to suggest a better charge extraction property of PEDOT:PSS that is conflict with its photovoltaic performance. Therefore, this puzzled phenomenon requires a deeper understanding on the interface associated with dielectric transport layers in perovskite solar cells towards generating a more complete guidance for future interface engineering. The early studies on organic solar cells have shown that the high-dielectric transport layer can facilitate the internal photovoltaic processes through stronger interfacial polarization [27-30]. In perovskite solar cells we can expect that a high-dielectric transport layer can have a stronger effect on internal photovoltaic processes due to the lower electron-hole binding energies in organo-metal hybrid perovskites.

In this work, we demonstrate that the NiOx HTL can simultaneously facilitate the bulk charge dissociation and suppress non-radiative/radiative recombination processes in the inverted perovskite solar cells [ITO/HTL/CH₃NH₃PbI₃/PC₆₁BM/Polyethylenimine, ethoxylated solution (PEIE)/Ag], which can give an efficiency up to 17.53% (16.15% in average). By combining magneto-photocurrent measurements under external bias, time-resolved and field-dependent PL measurements, and photoinduced capacitance-voltage characterizations, we demonstrate that these synergistic effects can be attributed to the enhanced built-in field that essentially results from both the reduced interfacial traps and increased interfacial polarization at CH₃NH₃PbI₃/NiOx interface as compared to CH₃NH₃PbI₃/PEDOT:PSS interface. Clearly, revealing the effects of NiOx HTL on the bulk charge dissociation, recombination, and collection provides a guidance on the rational design of interface engineering towards further advancement of photovoltaic actions in organo-metal halide perovskites.

2. Material and methods

2.1 Device Fabrication

All solar cells studied in this work were fabricated with the inverted structure of ITO/HTL/ $\text{CH}_3\text{NH}_3\text{PbI}_3$ /PC₆₁BM/PEIE/Ag as shown in **Fig. 1(a)**. The energy level diagram is schematically shown in **Fig. 1(b)**. The NiOx HTL was prepared by solution processing method according to the previous publications [22,25]. More specifically, an ethylene glycol solution containing 0.5 M nickel formate dihydrate with 1 molar ethylenediamine was stirred overnight at room temperature and then filtered with 0.45 μm nylon filters before using. The NiOx HTL was spin-cast on the precleaned ITO substrate at 4000 rpm for 90 seconds and then annealed at 300 °C in air for 60 minutes. Alternatively, the PEDOT:PSS HTL (4083, Heraeus, filtered with 0.45 μm PVDF filter) was spin-coated onto the ITO substrate at 4000 rpm for 60 s and then thermally annealed in air at 150 °C for 25 minutes. The precursor solution of $\text{CH}_3\text{NH}_3\text{PbI}_3$ (1 M) was prepared by dissolving equimolar $\text{CH}_3\text{NH}_3\text{I}$ and PbI_2 in a mixture solvent with γ -butyrolactone (GBL) and dimethyl sulfoxide (DMSO) (7:3, v/v) at 60 °C for 12 h in the nitrogen-filled glove box. The perovskite films were spin-cast on top of the HTL by a consecutive two-step process at 1000 rpm and 4000 rpm for 20 s and 40 s, respectively. The 400 μL toluene was dropped on top of the perovskite films at the 20th second of the second step [31]. The as-cast films were immediately annealed at 100 °C for 10 minutes. After cooling down, the PC₆₁BM layer (20 mg/mL in chlorobenzene) was spin-cast on top of perovskite layer at 1000 rpm for 60 s and followed by keeping the substrates in a covered Petri-dish for 45 minutes as solvent annealing. The PEIE layer (polyethyleneimine, ethoxylated solution with 0.02 wt% in anhydride 2-Propanol) was spin-cast on top of the PC₆₁BM layer at 5000 rpm for 60 s to modify the workfunction of Ag. The Ag layer was

thermally evaporated with the thickness of 100 nm under the vacuum of 6×10^{-7} torr on the PEIE layer. The device-working area was 0.1 cm^2 .

2.2 Measurements and Characterizations

The current density-voltage (J - V) characteristics of all perovskite solar cells were measured in a nitrogen-filled glovebox by using Keithley 2602 source meter under simulated sunlight (AM 1.5G, Thermal Oriel 96000 300 W, Newport). The magneto-photocurrent measurements were performed by recording the photocurrent as a function of magnetic field (B , ~ 900 mT), which was applied parallel to the device plane. The B -induced photocurrent change (%) is defined by $\frac{I(B)-I(0)}{I(0)} \times 100\%$, where $I(B)$ and $I(0)$ represent the photocurrents with and without B , respectively. Photoinduced capacitance-voltage characteristics were measured by a dielectric spectrometer (Agilent, E4980A) with an AC bias (50 mV, 3 kHz). The PL spectra were recorded by SPEX Fluorolog III spectrometer under the photoexcitation of 532 nm CW laser, while the PL lifetimes were characterized by time-resolved PL (TRPL) measurements with Streak camera (HAMAMATSU C10627). The samples for TRPL measurements were excited by the second harmonic wavelength at 515 nm from an Yb-doped fiber laser (TANGERINE, Amplitude System) with the fluences of $5 \mu\text{J}/\text{cm}^2$ and a repetition rate of 50 kHz. In order to resolve the full dynamics with high resolution and signal-to-noise ratio, the dynamics of the fluorescence were recorded on several time windows, from 5 ns up to 500 ns with the time resolution of 0.5% for each time window. The data was fitted with exponential **Eq. (1)**:

$$Fit(t) = \left[\sum_{i=1}^2 A_i e^{-t/\tau_i} \right] \otimes \frac{1}{\sigma\sqrt{2\pi}} e^{\left(-\frac{t^2}{\sigma^2}\right)} \quad (1)$$

Where A_i is amplitude, τ_i represents the lifetime, and σ is the temporal resolution.

3. Results and Discussions

3.1 Photovoltaic Characterizations

Fig. 1(c) presents the J - V characteristics of both NiOx and PEDOT:PSS based perovskite solar cells with the key photovoltaic parameters summarized in **Table 1**. We can see that using the NiOx HTL to replace the PEDOT:PSS HTL leads to a large enhancement on V_{OC} from 0.88 V to 1.01 V, and simultaneously increases the short-circuit current (J_{sc}) from 19.32 to 21.14 mA/cm², while a high fill factor ($FF \sim 0.75$) can be readily achieved in all devices. As a result, the power conversion efficiency (PCE) is improved from 12.8% to 16.0% in average. The efficiency of the optimized devices with NiOx HTL has reached 17.53%. The performance distribution over ten devices is summarized in supporting information **Fig. S1**. Both the NiOx and PEDOT:PSS based devices do not show any I-V hysteresis phenomenon, which suggests the high-quality of perovskite layers.

3.2 Effects of NiOx HTL on Dissociation

Recently, we have shown that magneto-photocurrent measurements combined with an external bias can be used as an in-situ technique to study charge dissociation and recombination in perovskite solar cells under device-operating condition [32,33]. This experimental method is based on the following arguments. First, the electron-hole pairs are formed in both singlets and triplets through the Coulomb capture of photogenerated carriers in organic-inorganic hybrid perovskites. Second, a magnetic field can shift the spin population between singlet and triplet electron-hole pairs[32], leading to the changes in photocurrent based on the fact that the singlet and triplet spin pairs have lower and higher dissociation rates due to allowed and forbidden transitions. Third, applying a reverse bias can facilitate the dissociation of the electron-hole pairs, quenching the magneto-photocurrent

signal. As a result, monitoring the critical bias required to completely quench the magneto-photocurrent allows evaluating the dissociation of electron-hole pairs under device-operating condition. **Fig. 2** shows the magneto-photocurrent at short-circuit condition, namely magneto-Jsc, in the NiOx and PEDOT:PSS based solar cells. Surprisingly, the NiOx-based device presents a negligible magneto-Jsc, whereas the PEDOT:PSS-based device shows an appreciable magneto-Jsc. Clearly, the negligible and appreciable magneto-Jsc imply that electron-hole pairs are sufficiently and insufficiently dissociated in NiOx and PEDOT:PSS based devices at short-circuit condition, respectively.

Interestingly, in the NiOx-based device when applying a forward bias (+1.0 V, close to its Voc) to weaken the built-in field (E_{bi}), the magneto-Jsc is recovered to become appreciable, as shown in **Fig. 3(a)**. On contrast, in the PEDOT:PSS-based device when applying a reverse bias (-0.12 V) to strength E_{bi} , the magneto-Jsc can be completely quenched, as indicated in **Fig. 3(b)**. This field-dependent magneto-photocurrent study provides the first evidence that the E_{bi} can indeed influence the charge dissociation in perovskite solar cells. More specifically, using the NiOx to replace PEDOT:PSS as HTL can enhance the charge dissociation through E_{bi} , consequently increasing the Jsc.

3.3 Effects of NiOx HTL on Built-in Field

Here, we use capacitance-voltage (CV) measurements in both dark and illumination conditions to evaluate the built-in potential (V_{bi}) in the NiOx and PEDOT:PSS based devices, respectively. Based on the CV characteristics (**Fig. 4 (a)** and **(b)**), the V_{bi} is calculated by adopting the classic Mott-Schottky model (**Eq. (2)** and **(3)**)[34,35].

$$C^{-2} = \frac{2(V_{bi}-V)}{A^2 e \epsilon \epsilon_0 N_A} \quad (2)$$

$$V_{bi} = \frac{Intercept}{|Slope|} \quad (3)$$

Where the C is capacitance; the V is the applied bias; the A is the active area; the e is elementary charge of an electron; the ε_r is the relative dielectric constant of the medium, the ε_0 is the permittivity in vacuum; and the N_A is the density of excited states.

As shown in **Fig. 4(c)** and **(d)**, the V_{bi} of the NiOx and PEDOT:PSS based devices are determined to be 1.06 V and 0.94 V in dark condition and 1.02 V and 0.90 V under one-sun condition, respectively. Clearly, using the NiOx as HTL increases the device V_{bi} in both dark and illumination conditions. In general, the built-in field is determined by both the energy difference between the anode/HTL and cathode/ETL interfaces and the bulk band offset in solar cells. In organic solar cells, the bulk band offset is established with strong electrical polarization at Donor:Acceptor interface, consequently functioning as the main parameter to determine the built-in field, namely band-offset model [36]. Similarly, in perovskite solar cells the built-in field is determined by the energy difference between anode/HTL and cathode/ETL interfaces and the bulk polarization from the grain boundary defects. We should note that, when the grain boundary defects are passivated, the built-in field is mainly controlled by the energy difference between anode/HTL and cathode/ETL interfaces in perovskite solar cells, similar to metal-insulator-metal (MIM) model. This means that using different transport layer can change the built-in field in perovskite solar cells. We should further note that the anode/ETL and cathode/ETL interfaces are a function of photoexcitation due to the interfacial accumulation of photogenerated carriers. As a result, the built-in field can be divided into static and dynamic components determined by the energy difference between anode/HTL and cathode/ETL interfaces and the interfacial accumulation of photogenerated carriers. In particular, the V_{bi} can be largely affected by the dynamic component, namely interfacial accumulation of photogenerated carriers [27,32]. Our early studies have shown that the V_{peak} shift with increasing photoexcitation intensity can reflect the interface-accumulation of photogenerated carriers in solar cells [32]. Specifically, smaller

and larger V_{peak} shifts correspond to less and more interface-accumulation of photogenerated carriers. As shown in **Fig. 4(a)** and **(b)**, it is found that increasing the photoexcitation intensity causes different V_{peak} shifts, 0.05 V and 0.12 V for NiOx-based and PEDOT:PSS-based devices. This suggests a reduced interface-charge accumulation when using NiOx to replace PEDOT:PSS, forming higher V_{bi} through a dynamic parameter in the NiOx-based device.

3.4 Effects of NiOx HTL on Non-radiative Recombination

In solar cells, the photogenerated carriers will inevitably undergo non-radiative and radiative recombination. The non-radiative recombination is a fast process caused by defects[37]. Through non-radiative recombination the excitons can quickly annihilate into deeply trapped carriers prior to dissociation, forming a photovoltaic loss[38-40]. In perovskite solar cells, the radiative recombination refers to a bimolecular behavior in which the excitons can be available for dissociation. Therefore, the non-radiative and radiative recombination disallows and allows the excitons for generating photovoltaic actions, respectively. Obviously, controlling the non-radiative/radiative recombination offers an important pathway to improve the photovoltaic actions in the PSCs. **Fig. 5(a)** shows the PL quenching of $\text{CH}_3\text{NH}_3\text{PbI}_3$ layer upon applying the NiOx and PEDOT:PSS HTLs. We can see that the NiOx/ $\text{CH}_3\text{NH}_3\text{PbI}_3$ interface leads to a weaker PL quenching but a higher J_{sc} as compared to the PEDOT:PSS/ $\text{CH}_3\text{NH}_3\text{PbI}_3$ interface (a stronger PL quenching but a lower J_{sc}). A similar phenomenon has been reported previously [22,41]. This puzzled phenomenon brings an important question on how the NiOx HTL can influence the non-radiative and radiative recombination in the PSCs. As illustrated in **Fig. 5(b)**, the time-resolved PL studies suggest that the PL decay dynamics of both PEDOT:PSS/ $\text{CH}_3\text{NH}_3\text{PbI}_3$ and NiOx/ $\text{CH}_3\text{NH}_3\text{PbI}_3$ samples consist of fast and slow decay components, which have been ascribed to the trap-

assisted recombination and the bimolecular recombination[42,43]. The lifetime (τ_i) and amplitude (A_i), denoted in **Eq. (1)**, determined by curve fitting are given in **Fig. 5 (b)** for fast and slow components. Clearly, the NiOx/CH₃NH₃PbI₃ interface yields a much longer lifetime up to 20 ns, and fewer fast decay component (11%); while the PEDOT:PSS/CH₃NH₃PbI₃ interface gives a much shorter lifetime of ~ 6 ns and much more fast decay component (28%). It has been demonstrated that the trap-assisted recombination is present as a non-radiative recombination channel[44,45]. Therefore, our results provide the direct information that the NiOx/CH₃NH₃PbI₃ and PEDOT:PSS/CH₃NH₃PbI₃ interfaces exhibit lower and higher non-radiative recombination, leading to more and less excitons available for generating J_{sc}, respectively. Furthermore, we should note that the suppressed non-radiative recombination upon using NiOx HTL suggests a reduced density of trap states at HTL/ CH₃NH₃PbI₃ interface. The reduced density of trap states can be evidenced by the reduced dark current in the NiOx based device as shown in supporting information **Fig. S2**. Clearly, using the NiOx HTL can decrease the non-radiative recombination by reducing the interfacial traps, consequently increasing the J_{sc} in perovskite solar cells. We also note that a high-dielectric layer can facilitate the de-trapping of trapped carriers in organic solar cells due to interface-induced polarization [46], decreasing the effective density of interfacial traps. Here, the high dielectric constant may be partially responsible for the reduced interfacial trapping events in the NiOx based device.

3.5 Effects of NiOx HTL on Radiative Recombination

We should further note that measuring field-dependent PL can provide an evaluation on radiative recombination in perovskite solar cells [47]. In particular, the perovskite (CH₃NH₃PbI₃) layer possesses low electron-hole binding energies ranging from 37 meV to 50 meV [48,49]. With the low binding energies, we can expect that changing the built-in field by

applying an external bias can vary the exciton separation and consequently modifies the PL intensity. Essentially, stronger/weaker field-dependent PL reflects more/fewer excitons ready for radiative recombination. This method is based on the following arguments. First, the excitons involved in radiative recombination are available for generating photocurrent, noting that in the non-radiative recombination the excitons are not available for generating photovoltaic actions. Second, separating excitons is a field-dependent process in organo-metal halide perovskites due to low binding energies [48,49], consequently leading to a field-dependent PL. Here, we measure the PL intensity alternatively towards short-circuit and open-circuit conditions to understand how the NiOx HTL affects the radiative recombination in the $\text{CH}_3\text{NH}_3\text{PbI}_3$ layer. We can see in **Fig. 5(c)** that the PL intensity difference measured at short-circuit and open-circuit conditions shows larger and smaller values in the NiOx-based and PEDOT:PSS-based devices, respectively. Specifically, the PL intensity is decreased by 86 % in the NiOx-based device but by 62 % in the PEDOT:PSS-based device when switching from open-circuit to short-circuit condition. Equivalently, the NiOx-based device shows a stronger field-dependent PL as compared to the PEDOT:PSS-based device. Therefore, we can suggest that the NiOx HTL can also suppress the radiative recombination within available excitons under the influence of E_{bi} , thereby increasing the photovoltaic performance.

4. Conclusions

In summary, our bias-dependent magneto-photocurrent results show that using the high dielectric NiOx HTL can lead to a sufficient dissociation of electron-hole pairs in perovskite layer due to the stronger built-in field. This study reveals that the built-in field plays an important role in controlling the charge dissociation in organo-metal halide perovskites. Furthermore, our time-resolved measurement provides the direct information that the NiOx HTL can suppress the non-radiative recombination by decreasing interfacial traps at the

NiOx/CH₃NH₃PbI₃ interface. Suppressing the non-radiative recombination can essentially increase the fraction of excitons available for generating photocurrent. Furthermore, we observe that the NiOx HTL leads to a larger PL change in intensity upon alternatively measured at short-circuit and open-circuit conditions, presenting a stronger field-dependent PL in the NiOx-based device. This provides an experimental indication that the NiOx HTL can also suppress the radiative recombination through the stronger built-in field, enhancing the photovoltaic actions within available excitons. Moreover, our C-V studies confirm that the high dielectric NiOx HTL can increase the built-in field through static and dynamic parameters by reducing the interfacial traps and the interfacial accumulation of photogenerated carriers. Therefore, using the high dielectric NiOx HTL can lead to a photovoltaic enhancement through J_{sc} and V_{oc} in perovskite solar cells.

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Figures and Tables

Fig. 1. a) Device architecture. The HTL refers to NiOx or PEDOT:PSS; b) Energy diagram for the fabricated devices [ITO/HTL/ $\text{CH}_3\text{NH}_3\text{PbI}_3$ /PC₆₀BM/PEIE/Ag]; c) J - V characteristics measured under forward and reverse scans.

Fig. 2. Magneto- J_{sc} becomes negligible and appreciable in NiOx and PEDOT:PSS based devices values at short-circuit condition (zero external bias). Negligible and appreciable magneto- J_{sc} correspond to sufficient and insufficient dissociation of electron-hole pairs in NiOx and PEDOT:PSS based devices, respectively.

Fig. 3. Magneto-photocurrent upon adjusting built-in field by an external bias. a) In NiOx-based device magneto-photocurrent changes from negligible to appreciable value by decreasing built-in field through applying forward bias (+1.0 V); b) In PEDOT:PSS-based device magneto-photocurrent changes from appreciable to a negligible value by increasing the built-in field through applying a reverse bias (-0.12 V).

Fig. 4. Capacitance-voltage (CV) characteristics of solar cells with a) PEDOT:PSS and b) NiOx HTL under AM 1.5 G simulated sunlight with various intensities. c) and d) C^{-2} - V in dark condition and under one sun illumination for perovskite solar cells with PEDOT:PSS and NiOx HTLs, respectively. The built-in potential (V_{bi}) is derived from Mott-Schottky equation.

Fig. 5. a) PL spectra measured for NiOx/PVSK and PEDPT:PSS/PVSK double-layer samples. PVSK refers to the perovskite $\text{CH}_3\text{NH}_3\text{PbI}_3$. b) Time-resolved PL lifetime for NiOx/PVSK and PEDPT:PSS/PVSK double-layer samples. The PL decay dynamics can be described by a fast component ($\tau_f = 1.26 \text{ ns}$ and $A_f = 0.34$ for PEDPT:PSS/PVSK sample, while $\tau_f = 2.18 \text{ ns}$ and $A_f = 0.14$ for NiOx/PVSK sample) and a slow component ($\tau_s = 6.59 \text{ ns}$ and $A_s = 0.88$ for PEDPT:PSS/PVSK sample, while $\tau_s = 21.29 \text{ ns}$ and $A_s = 0.92$ for NiOx/PVSK sample). c) PL intensity is shown as a function of built-in potential by switching

from short-circuit condition towards open-circuit condition in NiOx and PEDOT:PSS based devices.

Table 1. The photovoltaic parameters derived from current-voltage characteristics measured with forward and reverse scans for NiOx and PEDOT:PSS based devices.

Type of HTL	Jsc (mA/cm ²)	Voc (V)	FF	PCE(%)
PEDOT:PSS(forward)	19.32	0.88	0.75	12.80
PEDOT:PSS(reverse)	19.10	0.89	0.77	12.98
NiOx(forward)	21.14	1.01	0.75	16.01
NiOx(reverse)	21.21	1.00	0.75	16.91

Vitae

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Professor Bin Hu received his Ph.D. from the Chinese Academy of Sciences under the supervision of Professor Xurong Xu in Condensed Matter Physics. He then worked as a postdoc at the Institute of Molecular Spectroscopy -- CNR, Bologna, Italy with Professor Carlo Taliani, and as research scientist at the University of Massachusetts/Amherst with Professor Frank Karasz. In 2002, he joined the faculty in the Department of Materials Science and Engineering at the University of Tennessee, Knoxville. His research includes spin-dependent processes in excited states, magneto-optic studies on photovoltaic and thermoelectric processes at different length scales, and lasing actions in ferroelectrically semiconducting materials.

Graphical Abstract