Photoluminescence Quantum Yield of Single-Wall Carbon Nanotubes Corrected for the Photon Reabsorption Effect

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Supporting Information

ABSTRACT: Photoluminescence (PL) from single-wall carbon nanotubes (SWCNTs) enables structural identification, but to derive the content rate of the specific chirality species it is necessary to know the quantum yield of each chirality. However, in the PL of SWCNTs, because the Stokes shift is small, the photon reabsorption effect is dominant and the apparent PL spectral shape and emission intensity are greatly modified depending on the concentration. This problem makes quantitative identification of SWCNTs by PL difficult. In this study, the concentration dependence of the PL of SWCNTs separated into a few chiralities was analyzed in detail, including the effect of reabsorption. It is clear that all changes in the PL spectrum occurring in the high concentration range can be explained simply by the reabsorption effect, and additional effects such as Coulomb interactions between SWCNTs can be negligible. Furthermore, a reliable quantum yield was derived from the emission intensity corrected for the reabsorption effect. The PL quantum yield varied with SWCNT chirality and exhibited a clear “family pattern”. This is consistent with the theoretical report showing that the chirality-dependent PL quantum yield is dominated mainly by relaxation by optical phonons from E_{22} to E_{11}.

KEYWORDS: Carbon nanotube, photoluminescence, quantum yield, photon reabsorption, chirality dependence

Single-wall carbon nanotubes (SWCNTs) have a tubular graphene structure and change their one-dimensional (1D) electronic properties depending on the atomic arrangement defined by a pair of chiral indices (n,m).† As a typical example of 1D confinement effects, semiconducting SWCNTs exhibit (n,m)-specific near-infrared E_{11} 1D-exciton photoluminescence (PL) for E_{22} excitation.‡ Using a pair of E_{22} PL emission and E_{11} excitation wavelengths, we can identify (n,m) species of the SWCNTs contained in a sample using the “family pattern” of SWCNTs. The PL intensity is also often used to deduce the abundance of specific (n,m) species in an as-grown or (n,m)-sorted sample.§–‖ In the case of the quantitative evaluation of (n,m) abundance, however, the PL quantum yield of each (n,m) species is necessary to derive the relative abundance of (n,m) species from the PL intensity. Previously, a theoretical study demonstrated that the PL quantum yield is strongly dependent on the structural factors of SWCNTs, such as diameter, chiral angle, family number (2n + m), and mod(2n + m, 3), where SWCNTs with mod(2n + m, 3) = 1 and 2 are called Type I and Type II, respectively.¶ In contrast, Tsybulskii et al. measured the PL cross section per carbon atom for a few (n,m) species using single-SWCNT microphotometry and revealed that the PL quantum yield generally increases with decreasing SWCNT diameter.© In addition, Mouri et al. also observed diameter-dependent PL quantum yields using several SWCNT sources, such as HiPco and CoMoCAT.© However, in the above experiments, the photon reabsorption effect was not considered for the estimation of PL intensities and further quantum yields. Because the Stokes shift is very small in this system, the photon reabsorption effect could be a serious problem. In fact, the reported experimental results did not reproduce the “family pattern” of the quantum yields predicted by theoretical calculations.© In this study, we investigated the effect of photon reabsorption on PL characteristics for (n,m)-sorted semiconducting SWCNTs. We have revealed that the apparent PL spectral change at high SWCNT concentrations is purely caused by a simple photon reabsorption effect, and additional effects such as Coulomb interactions between SWCNTs can be negligible. This simple situation enabled us to analyze intrinsic PL intensities. We obtained the PL quantum yields corrected for the photon reabsorption effect and then found a clear family pattern for the first time, which agrees well with the theoretical prediction.

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Because PL analysis for a mixed chirality sample is very difficult, we prepared Type I \((2n+m=19)\) species \((i.e., (7,5), (8,3), \text{and} (9,1))\), Type II \((2n+m=20)\) species \((i.e., (7,6), (8,4), (9,2), \text{and} (10,0))\), and the most often examined \((6,5)\) species, which were sorted using gel column chromatography with multiple surfactants.\(^{17-20}\) Different from previous gel
column chromatography with a single surfactant,\textsuperscript{21–24} in the
current sorting procedure, each \((n,m)\) SWCNT was dispersed
in different surfactant mixtures. To exclude the influence of the
surfactant on the PL intensity, the surfactants of all the
SWCNT solutions were replaced with the identical surfactant in
0.5 wt % sodium cholate (SC) using a cross-flow filtration
system (AKTA flux s, GE Healthcare) equipped with a hollow
fiber cartridge (surface area 26 cm\(^2\), Type 500 K, GE
Healthcare). After replacement of the surfactant, the SWCNTs
in each solution were concentrated using a centrifugal filter
unit (Amicon Ultra-15 with Ultracel-100 K membrane, Merck
Millipore) at 3000g. To prepare the SWCNT solutions with
different concentrations, the concentrated SWCNT solution
was diluted 2, 4, 8, 16, 32, 48, 64, and 128 times using a 0.5 wt
% SC solution.

Figure 1a shows a photograph of six concentrated SWCNT
solutions. The different colors of the solutions indicate
different \((n,m)\) components. The samples have light colors,
but the concentrations are high enough to show the typical
photon reabsorption effect. Figure 1b shows the optical
absorption spectra of diluted SWCNT solutions measured by
an ultraviolet–visible-infrared spectrophotometer (UV-3600,
Shimadzu) using a quartz cuvette with a path length of 10 mm.
Each spectrum exhibits a series of sharp absorption peaks,
corresponding to \(E_{11}\), \(E_{22}\), and \(E_3\) transitions, with significantly
low background absorption, which strongly suggests high-level
removal of metallic SWCNTs and amorphous carbon. The
SWCNTs contained in the samples were identified as \((9,1),
(8,3), (9,2), (6,5), (7,5), (8,4), (7,6),\) and \((10,0)\) based on
their \(E_1\) and \(E_2\) absorption peak wavelengths.\textsuperscript{25,26}Figure 1c shows PL excitation–emission spectral maps of the
diluted samples measured by a spectrophotometer (Nanolog, HORIZON-
BA) equipped with a liquid nitrogen-cooled InGaAs near-
infrared array detector. The peak positions were consistent
with the absorption spectra. As described later, these optical
absorption spectra and PL spectral maps were used to derive
the PL quantum yields because the \(E_{11}\) and \(E_{22}\) peaks of (8,3)
and (7,5) and \((8,4)\) could be subjected to analyses of their
entire \(E_{11}\) emission peak. Another possible reason is the
wavelength shift should also appear in the \(E_{11}\) emission peak,
while the full width at half-maximum of the \(E_{22}\) absorption peaks was independent of the
SWCNT concentration (not shown). These results indicate
that the optical absorbance at the \(E_{22}\) transition \(A_{(22)}\) is a good scale of the
SWCNT concentration. In contrast, the PL results exhibited different characteristics. Figure 2b shows the
maximum PL intensities and peak shifts for near-armchair
(7,6) and zigzag (10,0) SWCNTs as a function of \(A_{(22)}\), which
is proportional to the SWCNT concentration (Figure 2a).
In the low absorbance region (<0.3), i.e., in the low SWCNT
concentration region, the PL intensity increased with increasing \(A_{(22)}\), and the peak wavelength did not show a
large change. In the high absorbance region (>0.3), however,
the PL intensity decreased with increasing \(A_{(22)}\), and the peak
wavelength shifted to a longer wavelength. Figure 2c and d
shows the PL spectral of the (7,6) and (10,0) SWCNT solutions at each \(A_{(22)}\) corresponding to the plots in Figure 2b.
Here, to observe the spectral shape change, the PL spectra were
normalized by each maximum intensity. With increasing
\(A_{(22)}\), the apparent \(E_{11}\) PL peaks became broader, and the
shoulders at 1190 nm for (7,6) and at 1220 nm for (10,0)
SWCNTs became more obvious. In addition, \(E_1\) PL peak
splitting was observed for the (7,6) SWCNT at a relatively
high \(A_{(22)}\) value of 1.053. Similar spectral changes were also
observed for the other \((n,m)\) species at high \(A_{(22)}\) (Supporting
Information, Figure S2). This result demonstrates that the
optical absorbance is an important factor in the PL
characteristic of SWCNTs. Before performing a detailed
analysis, we note that all SWCNT samples showed unusual
maximal PL intensities at almost the same \(A_{(22)}\) value (0.25–
0.35) (Supporting Information, Figure S3). This unusual
phenomenon was caused by the optical path design of our PL
measuring system. Since our system is designed for a low
absorbance solution, the focal point of the PL collector lens is
at the center of the optical cell, which means that the detector
does not uniformly collect the PL signal from the full optical
cell but rather dominantly collects the signal from the center
of the optical cell.\textsuperscript{27} This difference is the reason why the PL
intensity decreased after reaching the maximum. More details
will be described below. In addition, the attenuation of the PL
intensity induced by photon reabsorption on the oxide-
induced \(E^{*}_{11}\) state\textsuperscript{28–30} is thought to be very weak, which is
consistent with the low optical absorbance at the wavelengths
of \(E^{*}_{11}\) (Supporting Information, Figure S4).

For the analysis of the PL intensities, we must consider
photon reabsorption\textsuperscript{14–16} because the \(E_{11}\) optical absorbance
is significantly large and the Stokes shift is very small. As the first
step, the reabsorbed optical spectrum \((I_{\text{reabs}}(\lambda))\) was obtained
by simply subtracting the experimentally observed PL
spectrum \((I_{\text{obs}}(\lambda))\) from the intrinsic spectrum \((I_{\text{int}}(\lambda))\),
\(I_{\text{reabs}}(\lambda) = I_{\text{int}}(\lambda) - I_{\text{obs}}(\lambda).\) For this analysis, we need the
intrinsic spectrum \((I_{\text{int}}(\lambda))\). In this work, we assumed that
reabsorption is negligible for the most dilute solutions that
correspond to \(A_{(22)}\) of 0.007 for (7,6) and 0.010 for (10,0) in
Figure 2c and d. We used the observed PL spectrum \((I_{\text{obs}}(\lambda))\)
for the most dilute solutions as the intrinsic PL spectrum
\((I_{\text{int}}(\lambda))\). We defined the normalized intrinsic spectrum
\((I_{\text{int}}^\text{normal}(\lambda))\), the normalized observed spectrum \((I_{\text{obs}}^\text{normal}(\lambda))\),
and the normalized reabsorption spectrum \((I_{\text{reabs}}^\text{normal}(\lambda))\) as follows:

\[
I_{\text{int}}^\text{normal}(\lambda) = I_{\text{int}}^\text{normal}(\lambda) / A_{(22)}
\]

\[
I_{\text{obs}}^\text{normal}(\lambda) = I_{\text{obs}}^\text{normal}(\lambda) / A_{(22)}
\]

\[
I_{\text{reabs}}^\text{normal}(\lambda) = I_{\text{reabs}}(\lambda) / A_{(22)}
\]
Figure 3a and b shows the normalized intrinsic PL spectra (I_{norm}(\lambda), red dashed curves) as well as the normalized observed spectra (I_{obs}(\lambda), black curves, refer to Figure 2c and 2d) for different concentrations of (7,6) and (10,0) solutions. The normalized reabsorption spectra (I_{reabs}(\lambda)) were obtained from them using eq 3 and are indicated in Figure 3 (blue dotted curves). The normalized reabsorption intensity increased with increasing SWCNT concentration. This increase is natural because reabsorption should be proportional to the SWCNT concentration. It is important to note that the spectral shapes of the intrinsic and the reabsorbed PL did not change for all measured concentrations (Supporting Information, Figure S5). Because the light source in the reabsorption process is the PL emission, the reabsorption spectrum is modified from the optical absorption spectrum by the light source spectrum. To compare the reabsorption spectrum with the optical absorption spectrum, we calculated the reabsorption spectrum from the measured optical absorption spectrum for the intrinsic PL emission spectrum. Figure 3c and d shows the reabsorption spectra calculated from the measured optical absorption spectra and intrinsic PL spectra, which perfectly agree with the reabsorption spectra obtained from the PL measurements.

This result means that the changes in the observed PL spectra are ascribed to the pure reabsorption process. The broadening and splitting of the PL spectra observed for high concentrations, as shown in Figure 2c and 2d, are well reproduced by a simple reabsorption effect. For the other (n,m) species, we obtained similar results with (7,6) and (10,0) species (Supporting Information, Figures S6--S11), where all PL spectral changes could be explained by the reabsorption effect.

In previous studies, the PL spectral change at high SWCNT concentrations was explained by the local environmental change around the SWCNTs, including the dielectric constant, exciton energy transfer, and exciton–phonon interaction. 

At least within the SWCNT concentrations examined in this work, however, the reabsorption effect enables us to fully interpret the A_{(j,22)}-dependent PL spectral changes, indicating that the differences caused by interactions between SWCNTS as described above are negligible.

We identified the quantum yield of each (n,m) SWCNT by analyzing the A_{(j,22)}-dependent PL spectral changes as described below. We considered the process of photon propagation into a uniform SWCNT solution in the PL measurement system: first, the excitation light is incident into the SWCNT solution; second, the generated emission light passes through the SWCNT solution; finally, the emission light is collected by a detector fixed at a constant angle against the excitation light direction. When the excitation condition is fixed, the integrals of I_{tit}(\lambda), i.e., the intrinsic PL peak areas, without reabsorption, should depend on A_{(j,22)} as follows:

$$\int I_{tit}(\lambda) \, d\lambda = \frac{\Omega}{4\pi} I_0 \phi (1 - \exp(-A_{(j,22)}))$$

where $\Omega/4\pi$ indicates the collection solid angle of the detector, $I_0$ indicates the excitation light intensity, and $\phi$ indicates the PL quantum yield of a specific (n,m) SWCNT (see details in the Supporting Information). The integrals of I_{obs}(\lambda) at low values of A_{(j,22)}, typically less than 0.1, can be approximated by the following equation (see details in the Supporting Information):

$$\int I_{obs}(\lambda) \, d\lambda = \frac{\Omega}{4\pi} I_0 \phi A_{(j,22)} - \frac{\Omega}{8\pi} I_0 \phi \left( \int 1 + \frac{A_{(\lambda)}}{A_{(j,22)}} f(\lambda) \, d\lambda \right) A_{(j,22)}^2$$

where $A_{(\lambda)}$ and $f(\lambda)$ indicate the absorption spectrum and the normalized intrinsic PL spectrum (whose areas are normalized to unity, $\int_{215} f(\lambda) = 1$), respectively. Importantly, because all raw intensity data have been corrected on the basis of the spectrum of the lamp and the collection solid angle was fixed,
the values of \( I_0 \) and \( \Omega/4\pi \) were treated as constant in these calculations.

Equation 5 incorporates the reabsorption effects by SWCNTs, but we need to incorporate the absorption of solvent, \( H_2O \) in near-infrared region. To clarify the influence of the solvent on the emission intensity, the original \( SC/H_2O \) solvent was replaced with \( SC/D_2O \) solvent. The concentrations of SWCNTs dispersed in \( SC/H_2O \) and \( SC/D_2O \) solvents were adjusted to be consistent by assuming that the absorption cross section of the specific (\( n,m \)) species is identical for \( SC/H_2O \) and \( SC/D_2O \) solvents (Supporting Information, Figure S12a). As a result, a significant decrease in the integrated PL intensity was observed for the \( SC/H_2O \) (denoted as \( I_{H2O} \)) compared with \( SC/D_2O \) (denoted as \( I_{D2O} \)) solvent (Supporting Information, Figure S12b). The rate of decrease (defined as \( \eta = (I_{D2O} - I_{H2O})/I_{D2O} \)) is obviously dependent on the emission wavelength within a range from 8.4 to 49.8%, which agrees with the absorption of \( H_2O \) (Supporting Information, Figure S13). By assuming that the absorption of \( D_2O \) is negligible, the corrected PL intensity can be estimated by incorporating the absorption of \( H_2O \).

To correctly evaluate PL quantum yield, the excitation and emission wavelengths of reference dye are very important to compensate the spectroscopic instrument functions. Indeed, Crochet et al. used Styryl-13 as the reference dye to obtain PL quantum yield of (6,5) SWCNTs, because both excitation and emission wavelengths of Styryl-13 match with that of (6,5). For the other \((n,m)\) species, therefore, appropriate reference dyes that match with their excitation and emission wavelengths should be prepared. In the present work, however, we used Styryl-13 as reference dye for all chiralities. Because the sensitivity of the InGaAs detector, transmittance of the monochromator, and efficiency of the other optical components in our PL measurement equipment were totally corrected by calibration function obtained by using a standard lamp, we can compare PL intensity of each species without farther corrections. Also, intensity of incident light was recorded by sensitivity-calibrated Si detector and PL intensity was normalized by the incident light intensity. (details are described in the optical measurements in the Supporting Information). In this condition, all emission intensities excited by any wavelength are comparable. Therefore, the Styryl-13 is considered to be suitable for evaluating the PL quantum yield of distinct \((n,m)\) SWCNTs in our case. As shown in Figure S14, Styryl-13 (Radiant Dyes Laser & Accessories GmbH, laser dye LDS 925) dissolved in methanol has a large Stokes shift (ca. 341 nm); therefore, we assumed that there is no reabsorption in a solution of Styryl-13. In other words, the integrated \( I_{obs} \) is identical to the integrated \( I_{int} \) for Styryl-13.

Figure 4 shows plots of the integrated \( I_{obs} \) intensity, i.e., PL peak area, for Styryl-13 as a function of the values of the absorbance peaks and plots for the eight \((n,m)\) species examined as a function of each \( A_{(122)} \), where the values for SWCNTs have been corrected with the absorption of the solvent using the decrease ratio in the emission intensity presented in Figure S13. As expected from eq 4, the integrated \( I_{obs} \) intensities of Styryl-13 increased nonlinearly with increasing values of the absorbance peaks. We fit eq 4 to the integrated \( I_{obs} \) intensities of Styryl-13 (blue dashed curve) and then determined the value of \( \Omega I_0 \phi/4\pi \); we estimated the value of \( \Omega I_0 \phi/4\pi \) \((4.1 \times 10^8)\) by adopting a quantum yield of 11% for Styryl-13, which was reported previously. For the SWCNTs, we fit eq 5 to the integrated \( I_{obs} \) intensities (red solid curves) and then determined the values of \( \Omega I_0 \phi/4\pi \). We estimated the quantum yields per unit of absorbed photons of the SWCNTs using the value of \( \Omega I_0 \phi/4\pi \) determined above (Table S1). In addition, we derived the integrated \( I_{int} \) intensities of the SWCNTs using the obtained parameters and eq 4 (blue dashed curves) because they could not have been measured experimentally. In addition, we calculated the curve of the observed PL intensity for the local volume at the center of the optical cell as a function of SWCNT concentration (Supporting Information, Figure S15a). As a result, the calculated curve reproduces our experimental observation that the PL intensity decreased after reaching the maximum, verifying our explanation. In addition, we found that the issue of focal collection does not affect the PL intensity for low SWCNT concentrations (Supporting Information, Figure S15b).

Since absorption cross section of each \((n,m)\) species is different, we have converted the PL quantum yields per unit of absorbed photons into that per carbon atom using a
to the chiralities with the same family number (2

function of the SWCNT diameter. Type I and Type II species are denoted as blue squares and red circles, respectively. The symbols corresponding

much stronger than that of (9,2) (Figure 1c), although their

the fact that the observed PL intensity of the (8,3) SWCNTs is

yield between (8,3) and (9,2) SWCNTs was consistent with

in previous studies, although the quantum yields of near-zigzag

yields of the near-armchair species are similar to those reported

along with the estimated PL quantum yields per carbon atom

were isolated from the same SWCNT dispersion prepared by

Since each (n,m) species of the SWCNTs used in this work

and E 11 than the LO phonon energy. 11 Although the

A _{22} values are not significantly different from each other

General, the PL intensities of zigzag species in the

as-grown SWCNTs were signiﬁcantly low compared to

which may be explained not only by the small abundance but also by the low quantum yield.

To examine the dependence of the PL quantum yields on

SWCNT structures, the quantum yields listed in Table 1 were

 plotted as a function of the SWCNT diameter (Figure 5a). The

PL quantum yield strongly changes depending on the (n,m)

indices for both Type I and Type II species. For Type I (2n + m = 19) species, i.e., (7,5), (8,3), and (9,1) species, no

monotonous chiral angle dependence was observed. For Type II (2n + m = 20) species, i.e., (7,6), (8,4), (9,2), and (10,0)

species, the PL quantum yields decreased with decreasing

chiral angle. Importantly, the PL quantum yields corrected on

the basis of photon reabsorption exhibit an obvious family pattern, which is similar to that of the PL intensities predicted

by the previous theoretical calculation (Figure 5c11), especially for chiral angle dependence in small diameter range.

Although the theoretical calculation shows smaller PL intensity for Type II species than for Type I mainly due to smaller induced

optical absorption in Type II SWCNTs, 13 our results show the PL quantum yield for Type I and Type II are comparable at small
diameter range. Family pattern of PL intensity was also reported by Tsyboulski et al. using microscopic PL measurements on

individual SWCNTs as shown in Figure 5b. 12 Their results also well reproduce theoretically predicted family behavior at slightly larger diameter range than our results. Interestingly, the family patterns in our present result (Figure 5a) and in the PL action cross sections (Figure 5b) complementarily reproduce theoretical results shown in Figure 5c. Theoretical calculation further showed that the PL intensity of semiconducting SWCNTs is mainly dominated by the relaxation process due to the longitudinal optical (LO) phonons from E 22 to E 11. 11 The significantly low PL intensities of (9,1) and (11,0) species are originated from their low relaxation rates due to smaller energy separation between E 22 and E 11 than the LO phonon energy. 11 Although the experimentally obtained PL quantum yield of (9,1) species is also very low, it is still comparable to that of (8,3) species, which is different from their PL intensities in theoretical calculations. This difference can be explained by the difference between the bare band structures obtained in theoretical

Figure 5. (a) Plots of the PL quantum yields of eight (n,m) SWCNTs as a function of SWCNT diameter. Error bars show the uncertainties shown in Table 1. (b) Plots of the PL action cross section from ref 12 as a function of the SWCNT diameter. (c) Plots of the PL intensity from ref 11 as a function of the SWCNT diameter. Type I and Type II species are denoted as blue squares and red circles, respectively. The symbols corresponding to the chiralities with the same family number (2n + m) are connected to guide the eye.

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calculations and the excitonic band structures obtained in experiments for (9,1) and (8,3) species if the PL quantum yields of the SWCNTs are also dominated by their relaxation rates. We also have to consider other possible reasons because the PL intensities and quantum yields of SWCNTs are highly influenced by their lengths, surrounding environments, and qualities. In the present experiment, the PL quantum yield was quantified for the SWCNTs with a specific length distribution in a surfactant solution; in contrast, in the theoretical calculation, the relative PL intensity was quantified for SWCNTs with a unit length in a vacuum. It should be mentioned that the chiral SC surfactant was used to disperse the SWCNTs in this work. In principle, chiral molecule or DNA may result in a difference in PL quantum yield between two enantiomers of the specific (n,m) SWCNTs due to handedness-dependent interactions with the chiral molecule. However, difference in the PL quantum yield between two enantiomers dispersed in SC solution was 4.2% that is smaller than the value of 9.8% for achiral sodium dodecyl benzenesulfonate (Supporting Information, Figure S16). In addition, the SWCNTs used in the theoretical calculation had perfect covalent sp² bonds between individual carbon atoms; in contrast, the SWCNTs measured in the present experiment actually have several defect sites induced by the SWCNT dispersion process. Although we performed the same dispersion process, the ease of introducing defects should be different for individual chiralities, which is likely to depend on the structure of the SWCNTs, such as the diameter. It is important to note that the PL intensity and quantum yield of the E₁ transition significantly decrease after the introduction of defects due to the change of the phonon lifetime. Previous studies have demonstrated that the intensity and position of the defect-derived PL peak changed depending on the structure of the SWCNTs. This change suggests the possibility that the defect-induced reductions in the PL intensity and quantum yield depend on the structure of the SWCNTs, but the detailed dependence is not investigated in this work. As mentioned above, therefore, the factors of SWCNT length, surrounding environment, and quality can account for the quantitative discrepancy between the experiment and theoretical calculation. However, a clear family pattern fully demonstrates that the diameter, chiral angle, and type play an important role in the PL quantum yield of semiconducting SWCNTs, which is very useful for a deeper understanding of the photophysical properties of SWCNTs.

In conclusion, we found that photon reabsorption highly modified the PL spectra of SWCNTs. By taking the photon reabsorption effect into consideration, we demonstrated that the PL quantum yields strongly depend on the SWCNT structure, including the family, diameter, and chiral angle, indicating that the apparent PL intensities do not represent the correct (n,m) distribution. For quantitative evaluation of the (n,m) distribution in SWCNT samples, not only the structure-dependent quantum yields obtained in this study but also the intensity correction for the reabsorption effect are found to be very important.

**ASSOCIATED CONTENT**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.9b04095.

Details of optical measurements, effects of enantiomers, PL spectral characteristics of eight (n,m) species, influence of solvent, estimated PL quantum yields per unit of absorbed photons, and fitting equation for integrals of observed PL intensity (PDF)

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**Notes**

The authors declare no competing financial interest.

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