Supporting Information

Principal Component Analysis of Surface-Enhanced Raman Scattering Spectra Revealing Isomer-Dependent Electron Transport in Spiropyran Molecular Junctions: Implications for Nanoscale Molecular Electronics

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S1. Assignment of vibrational modes for spiropyran and merocyanine

We conducted density functional theory (DFT) calculations for the isolated spiropyran molecules using Gaussian 16 software to assign the vibrational modes. The basis set was B3LYP and 6-31++G(d,p). The Raman shift was scaled using a scaling factor of 0.9650, as shown in Figure S1. In the SP form (Figure S1a), prominent peaks originating from $\nu(C-C)+\nu(C-C)D$, $\nu(C-C)A+\nu(C-C)D$, and $\nu(C=C)+\nu(C-C)D$ appear at 1537 cm$^{-1}$, 1592, and 1638 cm$^{-1}$, respectively.\textsuperscript{2-5} The labels A, B, C, and D indicate the aromatic rings of spiropyran, as shown in Figure S2 and S3a. The assignment of vibrational modes for the SP form is summarized in Table S1. For the MC form, prominent peaks originating from the $\nu(C-C)A+\gamma(N-CH_3)+\delta(C-(CH_3)_2)+\nu(C-N)B$, $\delta(C-H)C1-C2+\nu(C-C,C=O)D$, and $\nu(C-C)A+\nu(C-C)B+\nu(C-C)C1-C2+\nu(C-C)D$ appear at 1468, 1519, and 1586 cm$^{-1}$, respectively (Figure S1b). The appearance of the peak at 1519 cm$^{-1}$ and disappearance of the peak at 1592 cm$^{-1}$ in the case of the MC form are in agreement with a previous study.\textsuperscript{4} The assignment of the vibrational peaks of the MC form is summarized in Table S2. The Raman spectrum of cis-MC resembles that of trans-MC indicating that cis-trans conversion does not affect the discrimination.

![Figure S1](image-url). Simulated Raman spectra of Spiropyran (SP) and Merocyanine (MC) form using Gaussian 16. (a) SP form (red) and MC (blue) form. (b) trans-MC form (blue line) and cis-MC form (green line). The scale factor of 0.965 was applied to the x-axis of the spectra.
| Calculation | SERS | Vibrational mode |
|-------------|------|-----------------|
| 508(w)      | 507  | γ(C-C)B+γ(C-C)C |
| 732         | -    | Ring breathing of C and D, γ(C-C)A |
| 819(w)      | 805  | δ(C-H)A+δ(C-H)B+γ(C-H)C+γ(C-H)D |
| 869         | 884  | γ(C-H)A+γ(S-H)A |
| 1062        | 1069 | Ring breathing of A and D |
| 1209        | 1229 | Ring breathing of D |
| 1308        | -    | ν(C-C), ν(C-O)C+ν(C-C)D |
| 1342        | 1366 | ν(C-C)A+ν(C-N)B |
| 1537        | 1541,1546 | *ν(C-C)C+ν(C-C)D |
| 1592        | 1596,1608 | *ν(C-C)A+ν(C-C)D |
| 1638        | 1639 | *ν(C=C)C+ν(C-C)D |

Table S1. Vibrational mode assignment for the SP form.¹

¹The vibration modes marked by asterisks were used as markers for recognition.

Figure S2. Structure and the ring numbering of SP form.
Table S2. Vibrational mode assignment for the MC form.

| Calculation | SERS | Vibrational mode |
|-------------|------|------------------|
| 705(vw)     | -    | $\delta$(C-C)A+Ring Breathing B,D |
| 833(vw)     | 835  | $\gamma$(C-H)C2+$\gamma$(C-H)D |
| 921(vw)     | 917  | $\delta$(C-C)D+$\delta$(D-SH) |
| 1046(vw)    | -    | $\delta$(C-C)A+$\tau$(N-CH$_3$)+$\tau$(C-(CH$_3$)$_2$) |
| 1074(vw)    | -    | Ring breathing A+$\delta$(C-C)D |
| 1117        | 1112,1138,1155 | Ring breathing A+ B+$\tau$(N-CH$_3$) |
| 1235        | -    | $\delta$(C-H)C1-C2+$\delta$(C-H)D |
| 1290        | 1293 | $\delta$(C-H)A+$\delta$(C-H)C1-C2+$\nu$(C-C)D |
| 1322        | 1311 | $\delta$(C-H)C1-C2+$\nu$(C-C)D |
| 1333        | 1381 | $\nu$(C-C)A+$\tau$(N-CH$_3$) |
| 1468        | 1420 | $\nu$(C-C)A+$\gamma$(N-CH$_3$)+$\tau$(C-(CH$_3$)$_2$)+$\nu$(C-N)B |
| 1488        | 1505 | *$\gamma$(N-CH$_3$)+$\delta$(C-H)C1-C2+$\nu$(C-C,C=O)D |
| 1519        | 1523,1534 | *$\delta$(C-H)C1-C2+$\nu$(C-C,C=O)D |
| 1586        | 1569,1583 | *$\nu$(C-C)A+$\nu$(C-C)B+$\nu$(C-C)C1-C2+$\nu$(C-C)D |
| 1617        | 1597 | $\nu$(C-C)C1-C2+$\nu$(C-C)D |

*The vibration modes marked by asterisks were used as markers for recognition.

Figure S3. (a) Structure and the ring/atom numbering of trans-MC form. (b) Structure of cis-MC form.
S2. Categorization of the states using SERS spectra

We used the systematic algorithms described in the following sentences to recognize peaks originating from the SP and MC forms. First, the obtained SERS spectra were smoothed using a Savitzky–Golay filter. The noise intensity was defined as the maximum difference between the intensity of the smoothed curve and that of the raw data in the 10–150 cm⁻¹ region, where no vibrational peaks were observed. We then detected the peak for a single-molecule junction (SMJ) based on the assignment of the vibration mode, as mentioned in Section S1. Before fitting the peaks, we automatically detected the peaks using the SciPy module."Briefly, a peak was detected if its intensity was higher than that of two direct neighbors, and the detected peaks were selected based on the prominence parameter, which entails the intensity difference between the top and baseline of a peak."6

We then characterized the spectra based on the detected peaks. Specifically, we discriminated the SP and MC forms by defining the marker modes in the spectra with the SERS peaks. The SP form was defined by the ν(C=≡C)C⁺ν(C–C)D (1643 cm⁻¹), ν(C–C)A⁺ν(C–C)D (1600 cm⁻¹), or ν(C–C)C⁺ν(C–C)D (1552 cm⁻¹) vibrational modes. Further, the MC form was defined by the ν(C–C)A⁺ν(C–C)B⁺ν(C–C)C₁–C₂⁺ν(C–C)D (1582 cm⁻¹), δ(C-H)C₁–C₂⁺ν(C–C,C=O)D (1525 cm⁻¹), or ν(C–C)A⁺γ(N–CH₃)+τ(C–(CH₃)₂)+ν(C–N)B (1469 cm⁻¹) vibrational modes. Therefore, Figure 2a in the main text was assigned to the SP form, and Figure 2c in the main text was assigned to the MC form. Based on the categorization of the SERS spectra, we extracted the states originating from the spiropyran molecule. The number of states with at least two peak structures is 2,135 out of 27,192, corresponding to 8% of all measured conductance states. We used the data of these 2,135 states as reliable signals of the target molecule for the analysis of the SMJ. We then estimated the presence of such states for both the MC and SP forms. The number of states assigned to the SP and MC forms are 273 and 846, respectively. This means that the probability of occurrence of the MC form in an SMJ is 40%, whereas that of the SP form is 13%. Further, 1,013 states showed peaks originating from both the SP and MC forms; such peaks might originate from the rapid transition between the MC and SP forms during the SERS observation or from the intermediate state of the MC and SP forms (Table S3).

Table S3. Number of states assigned to the SP and MC forms.

| Category           | Number of states |
|--------------------|------------------|
| All states         | 2,135            |
| SP                 | 273 (13%)        |
| MC                 | 846 (40%)        |
| Both               | 1,013 (47%)      |
| Markers do not exist | 3 (0.14%)       |
S3. Time course of the conductance during the Raman measurements

The junction currents were continuously monitored at a bias voltage of 100 mV (Figure S4). The traces remained within the conductance region of the molecular junction for over 10 s without a rupture of the junction, indicating that the junctions formed in the present experiments possessed a sufficiently long lifetime to observe the Raman spectra. The stability shown in Figure S4 is attributed to the use of the lithographically fabricated electrodes in the MCBJ measurements.

Figure S4. Time courses of the conductance of the SP molecular junctions. Bias voltage of 100 mV.
S4. SERS and $I-V$ curves of the single-molecule junction for the SP and MC forms

Figure S5 shows the SERS spectra and corresponding $I-V$ curves for the SP (a, b) and MC forms (c-e), respectively. In the SP form, the vibrational mode originating from $\nu(C-C)A+\nu(C-C)D$ was observed at 1596–1608 cm$^{-1}$. For the MC form, the specific peaks determined by the experimental and calculation results are shown in Table S2. The peaks originating from $\delta(C-H)C1-C2+\nu(C-C,C=O)D$ and $\nu(C-C)A+\nu(C-C)B+\nu(C-C)C1-C2+\nu(C-C)D$, which are defined as the markers of the MC form, were observed at 1523–1534 and 1569–1583 cm$^{-1}$. The peak intensity fluctuated depending on the state. The assignments for the other vibrational modes are summarized in Tables S1 and S2.

Figure S5. SERS spectra and $I-V$ curves for the single-molecule junction. (a, b) correspond to the SP form, (c-e) correspond to the MC form. The conductance values are 23.2, 1.5, 9.2, 3.6, and 0.2 mG$_0$ for (a-e), respectively. The asterisks in the SERS spectra represent the markers for the discrimination of the SP and MC states.
S5. Isomerization between the SP and MC forms

Figure S6a and S6b show the time courses of the SERS spectra and I–V curves. In the SERS spectra shown in Figure S6a, the peaks at 1573 and 1587 cm⁻¹ assigned to the C–C stretching vibration vanished, and a peak at 1662 cm⁻¹ corresponding to the C=C stretching vibration of the pyran ring appeared. A similar temporal evolution was observed in the SERS spectra in Figure S5b: the peaks at 1590 cm⁻¹ disappeared, and the peak at 1631 cm⁻¹ appeared. Thus, the spectroscopic measurements revealed that the single MC molecule in the SMJ underwent isomerization to produce a single SP molecule. The simultaneously measured I–V curves reveal the changes in the transport properties of the SMJs concomitant with the isomerization. The conductance estimated from the I–V curves (Figure S6c and S6d for the I–V curves in Figure S6a and S6b, respectively) showed a sudden decrease upon the isomerization from MC to SP, which is consistent with the isomeric difference in electric conductance revealed by principal component analysis (PCA) (Figure 4). In addition, the conductance ratios between MC and SP in Figure S6c and S6d agree with each other and further with the ratio reported previously,⁷ which corroborates that the observed conductance changes arose from the isomerization. The conductance of the MC form at 3 s was rather small compared with that of the other MC forms. The vibration energy of the C=C stretching mode was located between those at 2 s and 3 s. This indicates the configurational change during the isomerization because the C–C stretching (observed at 1586 cm⁻¹ in the simulated spectra of the MC form) does not show a significant difference between the intermediate cis form and the transformation of the MC form. Thus, we conclude that SERS with simultaneous I–V measurements achieved the in-situ detection of the isomerization reaction in the SMJ and the concurrent changes in the electronic properties. Note that the conductance values of the isomers are different in the results in Figure S6c and S6d. Given the similar conductance ratios observed herein for the isomers, we attribute the variation in the conductance to the difference in the adsorption sites of the thiol linkers of the molecules.⁸

We will now comment on the mechanism of the isomerization reaction between MC and SP in SMJ. In solutions and crystals, the ring-opening reaction from the SP form to the MC form proceeds through UV light irradiation, whereas the ring-closing reaction from MC to SP proceeds through visible light irradiation or heating. Because the extinction spectra of our molecule showed peaks at 235 and 505 nm (Figure S7) and the intensity at 633 nm is negligible, it is improbable that the reaction directly occurred owing to excitation by the laser irradiation. Because the visible light irradiation on the nanogap induces localized surface plasmon resonance,⁸ nine unconventional reaction can be induced through two-photon absorption,¹⁰ local heating,¹¹ or injection of a hot electron or hole at the Au nanogap.⁸ ¹² We estimate the photothermal effect on the ring-closing reaction by assuming a simple Arrhenius equation with an activation energy of 76.5 kJ/mol.¹³ At the nanogap, assuming a laser power of 100 kW/cm², as employed in the present experiments, the local temperature increases by ~100 K.¹⁴⁻¹⁶ An enhancement of the reaction rate with an elevated temperature of 100 K is estimated by a factor of 2000. Therefore, the photothermal effect likely contributes to the ring-closing reaction in the SMJ, although additional effects can concurrently facilitate the reactions.
Figure S6 (a, b) Example of observed SERS spectra and $I-V$ curve of ring-closing photochemical reaction. (c, d) Conductance value corresponding to (a, b).
S6. UV-visible absorption spectrum of SP and protonated MC form

We measured ultraviolet-visible absorption (UV-Vis) spectrum of the deprotected spiropyran using the mixed solvent (THF:EtOH = 10:1 v/v, concentration: 20 μM) in the range of 800 – 190 nm with the UV-Vis spectrometer (V-650, JASCO Corporation, Japan). We obtained the baseline by measuring the spectrum of the THF. For the MC form, we added the hydrochloric acid to the solution of the SP form, then we obtained the protonated MC form. For the SP form, the absorption band was observed in 250 – 350 nm while that observed in 400 – 600 nm in addition to 250 – 300 nm for the MC form (Figure S7). Noticeably, no intensity is observed with the wavelength above 600 nm (Figure S7 inset).

Figure S7. The UV-visible absorption spectrum of SP and MC form.
**S7. Conductance histogram for the SP and MC forms based on the categorization**

Figure S8 shows the conductance histogram of the spiropyran single-molecule junction. The histogram was obtained by categorization based on the vibration mode of the SERS spectra. Particularly, the conductance histogram of the SP form is located around $10^{-2.3(\pm 0.3)} \, G_0$, whereas that of the MC form is located around $10^{-2.1(\pm 0.6)} \, G_0$. The MC form tended to exhibit a higher conductance. Although the central peak of the conductance was different for the SP and MC forms, the broad distribution of the histograms hindered the discrimination of the two isomers. This may be owing to the occurrence of other structural changes in the SMJs.

![Figure S8 1D conductance histogram of (a) SP form and (b) MC form.](image-url)
S8. Principle component analysis for SERS spectra of SMJs

The correlation between conductance and the structure of the spiropyran molecule, which is obscured by the configurational changes of the SMJ, was investigated using principal component analysis (PCA). PCA is a multivariate statistical analysis technique that can identify the major directions of variation in a given dataset.17-22 In PCA, the axes with the maximal variances are called principal components (PCs). To characterize the dataset, two components that are obtained by PCA should be focused on: “score” and “loading.” The scores represent the relationship between the samples (spectra) and PCs and are a projection of the original data points onto a given PC axis.18, 19, 23 The loadings represent the variables (Raman shifts) responsible for the separation observed in the scores plot.18, 23 Based on the PCs, one can extract several inter-correlated dependent variables from complex spectra.20, 22

For PCA, we analyzed the SERS spectra in the 1000 cm$^{-1}$–1700 cm$^{-1}$ region. The spectra were interpolated into 2 cm$^{-1}$ intervals using cubic spline interpolation. We used spectra that exhibited at least two peak structures. This means that we obtained a 350 × 2,135 data matrix. In this case, the rows represent the Raman shifts, while the columns represent the spectral numbers. To overcome the effect of noise, we standardized all spectra before PCA by subtracting the median of the data array from the data array of each spectrum and scaling the data to the range between the 10th and 90th quantiles. We then estimated the contribution rate, scores, and loadings for each component. The entire PCA was performed using the python module Scikit-learn.24 The scores and loadings of the PCs can be calculated as follows.

First, we define the sample variance covariance matrix $S$ as

$$
S = \begin{pmatrix}
S_{11} & \ldots & S_{1p} \\
\vdots & \ddots & \vdots \\
S_{p1} & \ldots & S_{pp}
\end{pmatrix} \quad (S1)
$$

where $S_{jk} = \frac{1}{n-1} \sum_{i=1}^{n} (y_{ij} - \bar{y}_j)(y_{ik} - \bar{y}_k)$ and $y_{im}$ is the normalized intensity of the $m$-th pixel of the $l$-th spectrum, and $\bar{y}_m$ is the average intensity of the $m$-th pixel. We note that $p$ is identical to the total pixel number.

Then, we solve the following eigen equation:

$$
Sh = \lambda h \quad (S2)
$$

We treat each eigenvector $h_n$ corresponding to eigenvalue $\lambda_n$ as the loading of the $n$-th PC (Equation S3). The norm of the eigenvectors is constrained to 1. Note that the loading is normalized because of the constraint of the eigenvectors. We constrain the order of the eigenvalues into $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_p \geq 0$. The loading represents the relationship between each PC and the variable before processing.

$$
\begin{align*}
  h_1 &= \begin{pmatrix} h_{11} \\ \vdots \\ h_{1p} \end{pmatrix},
  h_2 &= \begin{pmatrix} h_{21} \\ \vdots \\ h_{2p} \end{pmatrix},
  h_3 &= \begin{pmatrix} h_{31} \\ \vdots \\ h_{3p} \end{pmatrix},
  \cdots
  h_p &= \begin{pmatrix} h_{p1} \\ \vdots \\ h_{pp} \end{pmatrix}
\end{align*} \quad (S3)
$$

The variance ratio of the $k$-th PC, $V_k$, is defined using the eigenvalue $\lambda_n$ as follows:

$$
V_k = \frac{\lambda_k}{\sum_{k'=1}^{p} \lambda_{k'}} \quad (S4)
$$

Furthermore, the principal component score of the $j$-th spectrum for the $m$-th PC, $z_{jm}$, was calculated as follows:

$$
z_{jm} = h_{1m}y_{1j} + h_{2m}y_{2j} + \cdots + h_{pm}y_{nj} \quad (S5)
$$
The principal component score corresponds to the coordinate value of each spectrum for each PC axis. We extracted three components with large variance ratios: PC1, PC2, and PC3. The contribution rates of PC1, PC2, and PC3 were 0.20, 0.13, and 0.08, respectively. The low contribution rates of the main components might originate from the fluctuation of the SERS spectra which in turn may be due to structural fluctuations of the SMJs or the residual noise in the spectra.26, 27

The loadings with respect to the Raman shift are shown in Figure S9a–c. The loadings of PC1 do not show the prominent peak of the spiropyran molecule; however, those of PC2 and PC3 show peaks around 1520–1610 cm⁻¹ that correspond to the vibrational modes of spiropyran. The loading spectra indicate that PC2 and PC3 reflect the information of the spiropyran molecule, whereas PC1 reflects the background signal. To interpret the meanings of the PCs, we plotted a two-dimensional histogram of the score values and conductance for each PC. The scores of PC1 and PC2 did not correlate with the conductance. By contrast, the scores of PC3 exhibited a correlation with the conductance. The conductance dependency of PC3 indicates that it represents the intrinsic components of the conductance variations. We then analyzed the scores of PC3 for the SP and MC forms. Figure S10 shows a histogram of the scores of PC3 for SP and MC. The scores of the SP form are located around +1.0, while those of the MC form are located around -1.5. The prominent difference in the distribution of the scores of PC3, which depends on the conductance, indicates that PC3 explains the structural changes between the MC and SP forms that are concomitant with the conductance change. Notably, the conductance values decrease as the scores increase. The distribution of the score of PC3 indicates that the MC form tends to exhibit a larger conductance than the SP form. This conductance behavior is in agreement with previous conductance measurements of a spiropyran SMJ, as mentioned in the main text.7, 28, 29 PC2 may reflect the spectral changes mainly caused by the configurational change in the MC states on the Au surface. Although the contribution rate of the structural change between the MC and SP forms is high because of the stability of the MC forms on the gold surface, PC3 reflects the conductance change of a spiropyran SMJ. Therefore, the PCA of the SERS spectra reveals that the structural change from MC to SP induces the conductance change of the spiropyran SMJ.

Figure S9. (a-c) Loadings of PC1, PC2, and PC3, (d-f) 2D plot of the score vs conductance. The bin size is $10^{0.1} G_0$ for conductance and 0.267 for PCn score.
Figure S10. Score histogram for PC3. The red and blue bars represent the scores originating from the SP and MC, respectively. The categorization of the SP and MC follows the algorithm mentioned in Section S2.

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