Field-assisted thermionic emission toward quantitative modeling of charge-transfer mechanisms in contact electrification

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Abstract
Charge transfer mechanisms of contact electrification (CE) are essential for widening applications of the triboelectric nanogenerator, and thus are widely studied by scientists around the world. However, the quantitative modeling of CE, especially that between polymers, is still lacking. Herein, a model was proposed to describe the contributions from different mechanisms, including electron transfer and mass transfer in polymer/polymer CE through the field-assisted thermionic emission, where three groups of charge transfer mechanisms were distinguished by the polarity of the charge transfer and the corresponding electric field. The results indicated that the total generated charge in CE is actually much larger than the measured net surface charge, confirming the bidirectional material-dependent charge transfer mechanisms between two surfaces, which is meaningful for understanding the millennium puzzle in triboelectrification and provides a new perspective for promoting the applications to tailor surface charge generation.

KEYWORDS
charge-transfer mechanism, contact electrification, field-assisted thermionic emission, quantitative modeling, triboelectric effect

1 | INTRODUCTION

Contact electrification (CE), or triboelectrification, is a universally existed charge transfer phenomenon between any materials in contact. Because of the easily generated electrostatic charges and potential, CE is applied in electrostatic printing,\(^1\) electrostatic adsorption,\(^2\) and so forth. Recently, triboelectric nanogenerator (TENG) was proposed to scavenge environmental mechanical stimuli to be converted into electricity since 2012.\(^3\)–\(^8\) Based on the coupling effects of electrostatic induction and triboelectrification,\(^9\)–\(^12\) the charge generated from CE can be utilized through TENG. In the meanwhile, CE is usually not favored in industry because the high voltage generated by CE may cause electric breakdown in electronics and even fires,\(^13\)–\(^17\) leading to the property damage. Therefore, to manipulate CE in different situations, it is essential to understand charge transfer mechanisms quantitatively.\(^18\),\(^19\) Among all aspects, identifying the dominant charge carriers (electrons or mass) in the charge transfer process during CE that may vary according to different material systems,\(^20\) becomes an attractive and important topic and is thus keen by scientists.
Thermionic emission is highly related to the potential barrier of the charged surfaces and provides a new method to confirm the charge carriers by the extracted potential barrier height $\Phi$ based on Richardson’s law.\textsuperscript{21,22} Previous results by Xu et al. and our team have demonstrated the electron-transfer dominant mechanism in metal/dielectric CE.\textsuperscript{20,23–25} Such the electron-transfer mechanism was also proposed and demonstrated by multiple previous studies. In the meanwhile, some researchers insist mass transfer exists demonstrated by multiple previous studies. In the emission behaviors discovered by us\textsuperscript{20} indicated the existence of the bidirectional mass transfer in polymer/polymer CE. However, the quantitative model to describe the contributions from different mechanisms under diverse material systems is still lacking. Additionally, the electric field effect on $\Phi$ was ignored in previous reports,\textsuperscript{33–35} affecting the accuracy in data analysis and modeling. To quantitatively verify the components or the contribution ratios of different charge transfer mechanisms, further studies should be conducted on the thermionic emission of the CE surface with the field effect considered.

Herein, the field-assisted thermionic emission was utilized to quantitatively evaluate the ratios contributed from different charge transfer mechanisms for polymer/polymer pairs through TENG, where the potential barrier height of different polymer/polymer pairs can be obtained from the experimental results, demonstrating that the total generated positive and negative surface charge is much larger than the net surface charge. Additionally, the charge transfer processes between the triboelectric surfaces, including the electron transfer and mass transfer, are concluded to be bidirectional during CE. Besides, a model for calculating the contribution ratios of different charge transfer mechanisms was established and the contribution ratios from the positive and negative charge transfer were derived, which will be of great significance for understanding the millennium puzzle in CE mechanisms in the future.

## EXPERIMENTAL SECTION

### 2.1 Fabrications of TENG

For the metal/PTFE contact-separation (CS) mode TENG, top metal strips of titanium (Ti), stainless steel (SUS304) are commercial products with 0.1 mm in thickness. Electrode on the back side of the PTFE was silver with a thickness of 300 nm deposited by electron-beam evaporation. Electrodes of TENG are placed on $\text{Al}_2\text{O}_3$ plates by clips. For the polymer/polymer CS mode TENG, PTFE/PTFE, PC/PC, FEP/FEP, Kapton/FEP, PC/PTFE, PC/FEP, PTFE/FEP pairs were employed where the identical polymer pairs were conducted as the reference compared with metal/polymer TENG. Additionally, a 300-nm-thick silver layer was deposited by electron-beam evaporation on polymer layer as the back electrode. Conducting wire of nickel is attached on the TENG by clips. All CS mode TENGs used in experiments are in the same size of 30 mm $\times$ 50 mm, and polymers are all commercial products with the thickness of 50 $\mu$m except the comparison pair Al/Kapton with a thickness of 15 $\mu$m.

### 2.2 Construction of the experimental system

The whole experiments were conducted in a commercial oven purchased from Standhill, where a hole of 5 cm in diameter was dug at its right side. The working temperature of the oven is up to 573 K $\pm$ 5 K with the error of 1 K. CS mode TENG is placed at the center of the oven, which was fixed by clips on the designed steel bracket. $\text{Al}_2\text{O}_3$ plates of 1 mm were employed in the middle of TENG and substrates as insulating layer with excellent heat conductivity. A connector of aluminium is designed to transfer the motion driven by the linear motor to the TENG. Nickle wire was connected to Keithley 6514, which was utilized to measure the short-circuit charge transfer ($Q_{SC}$) (triboelectric surface charge) with sampling rate of 100. The linear motor was placed on a small optical table with proper height to fit the transmission structure.

### 2.3 Operational process of the experiment

For the CS mode TENG experiments, to exclude the charge compensation during continuously charge measurement that affect the charge decay, the initial intimacy of the two materials in contact was adjusted to ensure negligible charge generation (only at nC or sub-nC scale). The initial $Q_{SC}$ at room temperature of different tribo-pairs was controlled at a constant value by the rubbing of nitrile butadiene rubber (NBR) with the negative charged film. Here, NBR was utilized to compensate the surface charge of polymers due to its extraordinarily excellent wear-resistance as demonstrated in previous study, thus little NBR debris will be introduced to the polymer film during rubbing. After realizing the controlled value of $Q_{SC}$, the TENG was hold on at contact
condition, and then the oven started to heat up until the target temperature. Then, the $Q_{SC}$ variation of TENG was recorded under continuous CS operations.

The residual $Q_{SC}$ on each tribo-pair surface was immediately recorded after heating up to the target temperature to analysis the relationship between charge decay and system temperature. The operational temperature range was limited by few charges remained on the surface as well as the working temperature of polymers at a high temperature, about 453–473 K for all tribo-pairs.

### 2.4 Data analysis for extracting the potential barrier height

These results were analyzed based on the Richardson's law:

$$ J = \lambda A_0 T^2 e^{-\frac{\Phi}{kT}} \left[ e^{\frac{\Delta W}{kT}} - 1 \right], \quad (1) $$

where $J$ is the current density affected by the thermionic emission; $\lambda$ is the material-specific correction factor; $A_0$ is Richardson constant of a free electron; $T$ is the temperature; $\Phi$ is the measured potential barrier height; $k$ is Boltzmann constant; and $\Delta W$ is the potential barrier height variation due to the surface electric field $E$. When $E$ is opposite to the thermionic emission direction, $\Delta W > 0$. Assuming that $\Delta W \propto E$, where $E \propto Q_{SC}$. Then, we may assume that $\Delta W = \frac{\lambda M}{\lambda} Q_{SC}$ ($\lambda_M$ is a constant related to the emission material). The term $\left[ e^{\frac{\Delta W}{kT}} - 1 \right]$ can be replaced as $\frac{\Delta W}{kT}$ because the term $\frac{\Delta W}{kT}$ is very small.

By assuming $J = \frac{1}{A} \frac{dQ_{SC}}{dt} = SQ_{SC}$, then

$$ S = \frac{\lambda M A_0}{k} T e^{-\Phi/kT}. \quad (2) $$

The variation of $Q_{SC}$ of tribo-pairs with the time at typical temperature due to thermionic emission followed exponential decay as follow:

$$ Q_{SC} = Q_{SC0} e^{-SA_t}, \quad (3) $$

where $Q_{SC0}$ is the initial value of $Q_{SC}$; and $A$ is the effective contact area.

Therefore, the equation can be derived as:

$$ \ln \left[ \frac{J}{A_0 T} \right] = -\frac{\Phi}{kT} + \ln \left[ \frac{\lambda M}{k} Q_{SC} \right]. \quad (4) $$

Thus, the $\Phi$ can be extracted through the fitted slope.

### 3 RESULTS

Although previous studies demonstrated that electron transfer is dominant in metal/polymer CE, the complicated mechanism of polymer/polymer CE remains unclear. Particularly, attributed to different mechanical properties and electrical properties of polymers, the polymer/polymer CE may highly depend on the material type, where the contribution ratios of electron transfer and mass transfer may vary a lot with different materials, and thus the quantitative model is required. To distinguish the electron transfer and mass transfer mechanisms, thermionic behaviors of TENG with different polymer pairs have been studied in this study, where $\Phi$ was derived by applying Richardson’s law based on the time-dependent and temperature-dependent variations on the surface charge due to the thermionic emission. As the designed experimental system illustrated in Figure 1A, A TENG can be placed in an oven and driven by a linear motor. Time-dependent and temperature-dependent short-circuit charge transfer $Q_{SC}$ can be measured by a coulometer, which is considered as the surface charge that can reflect the thermionic behavior, where the photograph of the experiment setup was shown in Figure S1. Operational process of this experiment is similar to previous studies, as summarized in Section 2.3. As an example, the residual surface charge on the surface of pre-charged PTFE/PTFE pair while reaching the target temperature $T$ was recorded, as shown in Figure 1B. The residual charge decayed with the increased $T$ due to the thermionic emission. The charge evolution against time and temperature of the PTFE/PTFE pair was summarized in Figure 1C, reflecting that the charge decay rate increased with temperature increasing. Such the charge decays exponentially, with the fitting results of different $T$ and material pairs summarized in Figure S2.

The mass transfer of charges exists along with the breakage of chemical bonds. Considering the random breakage of chemical bonds, the transferred material during the mass transfer should be either positively or negatively charged and is bidirectional between both surfaces. Additionally, considering the different electron affinities of local atoms in different molecular chains during CE, the electron transfer should be bidirectional as well. Therefore, the polymer/polymer CE process is illustrated in Figure 1D, with six potential CE mechanisms including the bidirectional electron transfer and four types of mass transfer. Here we assume polymer A was always the positively charged surface after CE. The complete CE model is elaborated as follows, as shown in Figure 1E. Considering that the thermionic emission is
only related to $\Phi$ of the negative surface that involves electrons, the mechanisms include: (1) Electron transfer from A to B with the $\Phi$ depending on the surface B ($\alpha$ as the contribution ratio); (2) Negatively charged mass transfer from A to B with the $\Phi$ depending on the material A ($\xi$ as the contribution ratio); (3) Positively charged mass transfer from A to B ($\kappa$ as the contribution ratio), with $\Phi$ depending on the material A; (4) Electron transfer from B to A with the $\Phi$ depending on the material A ($\iota$ as the contribution ratio); (5) Negatively charged mass transfer from B to A ($\beta$ as the contribution ratio), with $\Phi$ depending on the material B; (6) Positively...
charged mass transfer from B to A ($\gamma$ as the contribution ratio), with $\Phi$ depending on the material B. It should be noticed that $\alpha$ and $\gamma$ cannot be distinguished by the designed experiment since through $\Phi$ only the original thermionic emission material can be identified, while the origin of the electrons cannot be distinguished. Similar situation exists in the contribution ratios $\kappa$ and $\iota$, which cannot be distinguished either.

To identify the contribution ratios in polymer/polymer CE, thermionic emission behaviors of seven polymer pairs, including PTFE/PTFE, PC/PC, FEP/FEP, Kapton/FEP, PC/PTFE, PC/FEP, PTFE/FEP, were studied through TENG as the tool, and Ti/PTFE and SLS/PTFE were used to investigate the $\Phi$ of PTFE as the reference. The time-dependent and temperature-dependent $Q_{\text{SC}}$ variation of each material pair was measured under continuous CS motion with the temperature range of around 333–443 K. The charge evolution of all material pairs was summarized in Figure S3 and the corresponding exponential charge decay was shown in Figure S2. These results were then analyzed based on Richardson’s law, with details for the derivation depicted in Section 2, and the $\Phi$ can be extracted from the following equation based on the experimental results:

$$\ln \left( \frac{J}{A_0 T} \right) = -\frac{\Phi}{kT} + \ln \left( \frac{M}{kT} Q_{\text{SC}} \right).$$  \hspace{1cm} (5)

Here $J$ is the overall current density by the thermionic emission that can be determined through the experimental results. Derivations of Equation (5) are depicted in Section 2.

Thus, the $\Phi$ can be extracted through the fitted slope. Plots of $\ln(J/A_0/T)$ against $1/T$ with measured results for the 9 tribo-pairs were linearly fitted and summarized in Figure 2. For the material pairs involving the polymer with glass transition temperature $T_g$, the $T$ range was divided into two parts with linearly fitting on each part ($T$ range lower than $T_g$ as part I and $T$ range over $T_g$ as part II) with the corresponding fitted slopes marked beside the fitted line, where the temperature fitting range for each part of different polymers was summarized in Table S1. The results indicated that $\Phi$ from the identical polymer pair (PTFE/PTFE, PC/PC, etc.) is close to that from metal contacting with corresponding polymer, which is consistent with our previous results.\(^{20}\)

The $\Phi$ of polymer pairs were calculated from the experimental results and summarized in Table 1, and the $\Phi$ from metal/polymer pairs were summarized in Table S2, with bar graph reflecting the results summarized in Figure S4. The extracted equivalent potential barrier height $\Phi$ from polymer/polymer pairs ($\Phi_{A/B}$) were more complicated, which were quite different from that of identical material pair A ($\Phi_A$) or B ($\Phi_B$), indicating that both mass and electron transfer mechanisms may co-exist in the polymer/polymer CE, which is consistent with the models illustrated in Figure 1D,E.

It should be noticed that the extracted $\Phi$ should be comprised of the theoretical potential barrier height $W$ and the barrier variation $\Delta W$ as affected by $E$, due to impact of the electric field. Previous studies usually considered $W$ as the $\Phi$,\(^{24}\) ignoring the field effect, which may affect the accuracy for calculating the contribution ratios. By considering the impact from the electric field, the $\Phi$ should be given as:

$$\Phi = W \pm \Delta W.$$  \hspace{1cm} (6)

Therefore, Richardson’s law is modified based on the field effect as follows:

$$J = \lambda A_0 T^2 e^{-\frac{W + \Delta W}{kT}} e^{\frac{\Delta W}{kT} - 1}.$$  \hspace{1cm} (7)

Namely,

$$J = \lambda A_0 T^2 e^{-\frac{\Phi}{kT}} e^{\frac{\Delta W}{kT} - 1}.$$  \hspace{1cm} (8)

where $W$ is the potential barrier height at the thermodynamic equilibrium (when the applied voltage equals to 0). The polarity of $\Delta W = \eta_M W$ depends on the direction of thermionic emission and $E$, where $\eta_M$ is defined as the field-effect factor which slightly varies in different materials. The $E$ inside each polymer layer in different TENGs were calculated as follows, where the derivation is described in Supporting Information Note S1 in detail. Here we only discuss the field effect in the CS mode TENG.

The electric field $E$ in metal/polymer and polymer/polymer pairs as measured in CS mode TENG was illustrated in Figure 3A(i) and (ii), respectively. For the metal/dielectric CS mode TENG, the $E$ in the dielectric layer is derived as:\(^{10,24}\)

$$E = -\frac{C_1(x) Q_{\text{SC}}}{C_2 \varepsilon_0 A} \propto Q_{\text{SC}},$$  \hspace{1cm} (9)

where $C_1(x)$ is the capacitance of the air gap between the triboelectric surfaces; $C_2$ is the capacitance of the dielectric layer; and $\varepsilon_0$ is the vacuum permittivity. The negative sign means that the $E$ shows the opposite polarity to the output voltage, indicating that $E$ improves the potential barrier.
FIGURE 2  Results of thermionic emission measured from TENG. Plots of $\ln(J/J_0/T)$ against $1/T$ with measured results in dots and linear fitted results in line, for (A) SLS/PTFE; (B) Ti/PTFE; (C) PTFE/PTFE; (D) FEP/FEP; (E) PC/PC; (F) Kapton/PTFE; (G) PC/PTFE; (H) PC/FEP; (I) PTFE/FEP. In Figure (D)-(I), the plots were partially fitted in the temperature range lower and higher than the glass transition temperature, respectively. The slope was marked beside the corresponding fitted line.

TABLE 1  Measured $\Phi$ of polymer pairs extracted from the experimental results

| Positive | Negative | Kapton | PC I | PC II | PTFE I | PTFE II | FEP I | FEP II |
|----------|----------|--------|------|-------|--------|---------|-------|-------|
| PEEK I   | 0.4385   |        |      |       |        |         |       |       |
| PEEK II  | 2.1516   |        |      |       |        |         |       |       |
| Kapton   | 0.8111   | 0.5510 | 1.3480| 0.2002| 0.7620 | 0.3286  |       |       |
| PC I     | 0.2766   |        |      |       |        |         | 0.4742| 0.3033|
| PC II    | 1.0353   |        |      |       |        |         | 1.5679| 0.9926|
| PTFE I   |         |        |      |       | 0.6508 | 0.2555  |       |       |
| PTFE II  |         |        |      |       | 0.6508 | 0.5085  |       |       |
| FEP II   |         |        |      |       |        |         |       | 0.5372|
For the dielectric/dielectric CS mode TENG, $E$ exists in both dielectric layers:

$$E_1 = -\frac{Q_{SC}}{\varepsilon_0 \varepsilon_A A} \propto Q_{SC},$$  \hspace{1cm} (10)$$

$$E_2 = -\frac{Q_{SC}}{\varepsilon_0 \varepsilon_B A} \propto Q_{SC},$$  \hspace{1cm} (11)$$

where $\varepsilon_A$ and $\varepsilon_B$ are the permittivity of polymers A and B, respectively; $E_1$ and $E_2$ are the electric field inside polymers A and B, respectively.

Equations (9–11) indicate that $E$ inside each polymer is proportional to $Q_{SC}$, however, the polarity of $\Delta W$ affected by the $E$ is different, depending on the relative direction between $E$ and the thermionic emission. For example, $E$ is opposite to the thermionic emission direction in metal/polymer CS mode TENG, as shown in Figure 3A(i), so the sign is positive considering the electron is negatively charged. Similarly, for the polymer/polymer CS mode TENG in Figure 3A(ii), $E_1$ reduces the potential barrier but $E_2$ improves the potential barrier, resulting in different signs. The surface states model for illustrating the field-assisted thermionic emission in metal/polymer CE was established, as illustrated in Figure S5. The field-assisted thermionic emission provides a potential method to identify the existence of mass transfer in the identical polymer pairs. As shown in Figures S4 and S6, $\Phi$ from identical polymer pairs were always slightly smaller than those from metal/polymer pairs, probably attributed to the thermionic emission from the positively net charged surface that reduces the potential barrier height, as described in Supporting Information Note S2.

To investigate the mechanism quantitatively, further experiments were conducted and analyzed. Figure 3B,C summarized the charge variation and linearly fitted results with the varied thickness of Kapton film from 50 to 15 $\mu$m. It is noted that when the thickness of the dielectric layer and the air gap change, the $\Phi$ from metal/Kapton pairs almost keeps invariant, but when $Q_{SC}$ changes from 90 to 130 nC, the $\Phi$ is obviously enlarged as shown in Figure 3D,E, which is attributed to the enhancement of $E$ inside PTFE, reflecting that $E$ is mainly dependent on $Q_{SC}$, which is consistent with Equations (9–11). Therefore, with the $E$-field-assisted thermionic emission considered, a more quantitative model for calculating the contribution ratios of different charge transfer mechanisms was established. Besides, the existence of the discharge effect was indicated by the sudden change in charge at a higher $Q_{SC}$ of 130 nC.
because of the obviously enhanced local electric field, as shown in Figure S7.\textsuperscript{37} As comparison, the charge decay by the thermionic emission follows a continuously exponential decay.\textsuperscript{20} To avoid this discharge effect, the initial charge of different material pairs was controlled around 80 nC, resulting in continuous charge evolution as shown in Figures S2–S3 without any obvious sudden charge change, so the discharge effect can be ignored.

By considering the field effect in polymer/polymer CE as proposed in Figure 3A, the field-assisted thermionic emission can be quantitatively evaluated to determine the contribution ratios based on Richardson’s equation:

\begin{equation}
J_{A/B} = \frac{\lambda_{A/B}A_0}{k}e^{-\frac{\Phi_{A/B}}{kT}}Q_{SC} = Q_{SC}S_{A/B},
\end{equation}

where the subscript A/B represents the employed polymer pair. The detailed derivation of Equation (12) was described in Section 2. Here, \( \Phi_{A/B} \) was extracted from experimental results by Equation (5) and \( S_{A/B} \) was obtained from the exponential \( Q_{SC} \) output. Current density contributed by each mechanism in Figure 1E can be distinguished by equations as stated below.

For thermionic emission from surface B, mechanisms 1, 5 and 6 correspond to following current densities:

\begin{equation}
J_\alpha + J_\gamma = \frac{\lambda_BA_0}{k}T^2e^{-\left(\frac{W_\alpha+\Delta W_\beta}{kT}\right)}Q_{SC} = Q_{SC}S_B (13)
\end{equation}

\begin{equation}
J_\beta = \frac{\lambda_BA_0}{k}e^{-\left(\frac{(1-\eta_\beta)W_\beta}{kT}\right)}Q_{SC} = \beta Q_{SC}S_{A/B}.
\end{equation}

Here, because \( \alpha \) and \( \gamma \) cannot be distinguished by the designed experiment as discussed before, the thermionic emission current by the two mechanisms is combined in Equation (13). Here \( \Delta W \) of a single charge transfer mechanism is determined by the corresponding \( E \) and \( E \propto Q_{SC} \), so the current density from a single charge transfer mechanism is derived as approximately proportional to pristine \( Q_{SC} \), while the material factor \( \lambda_B \) is determined by the certain emission material.

Additionally, mechanisms 2, 3 and 4 (thermionic emission from surface A) can be derived as:

\begin{equation}
J_\xi = \frac{\lambda_AA_0}{k}e^{-\left(\frac{(1-\eta_\xi)W_\xi}{kT}\right)}Q_{SC} = Q_{SC}S_A (15)
\end{equation}

\begin{equation}
J_\kappa + J_\iota = \left(\frac{\lambda_BA_0}{k}T^2e^{-\left(\frac{(1-\eta_\kappa)W_\kappa}{kT}\right)}Q_{SC} = (\kappa + \iota)Q_{SC}S_{A/B}.
\end{equation}

\begin{equation}
J_{A/B} = J_\alpha - J_\beta + J_\gamma + J_\xi - J_\kappa = \alpha J_{A/B} - \beta J_{A/B} + \gamma J_{A/B} + \xi J_{A/B} - \kappa J_{A/B}.
\end{equation}

In the other word, \( \alpha + \gamma - \beta + \xi - \kappa = 1 \). Unfortunately, only the sum of \( \beta + \kappa + \iota \), namely, the total reverse charge transfer, can be determined based on the experimental results, while the value of each contribution ratio cannot be distinguished due to lack of information for the two field-effect factors \( \eta_A \) and \( \eta_B \). The contribution ratios by the term of \( \alpha + \gamma \), \( \xi \) and \( \beta + \kappa + \iota \) were summarized in Table 2.

It should be noticed that both the total contribution ratios from the positive charge (\( \alpha + \gamma + \xi \)) and negative charge (\( \beta + \kappa + \iota \)) are larger than 1. This indicates that the charge generated by the polymer/polymer triboelectric effect always involves both positive and negative charges, while the total positive plus negative charge amount is much larger than

\begin{equation}
J_{A/B} = \frac{\lambda_BA_0}{k}T^2e^{-\left(\frac{(1-\gamma_\beta)W_\beta}{kT}\right)}Q_{SC} = \beta S_{A/B} Q_{SC} = \beta.
\end{equation}

\begin{equation}
\frac{\lambda_BA_0}{k}e^{-\left(\frac{(1-\eta_\beta)W_\beta}{kT}\right)}Q_{SC} = \beta S_{A/B} Q_{SC} = \beta.
\end{equation}

Combining the Equations (15)–(16), the contribution ratios of mechanisms 2–4 are:

\begin{equation}
Q_{SC}S_A = \xi Q_{SC}S_{A/B} \Rightarrow \xi = \frac{S_A}{S_{A/B}},
\end{equation}

\begin{equation}
\frac{\lambda_BA_0}{k}e^{-\left(\frac{(1-\eta_\beta)W_\beta}{kT}\right)}Q_{SC} = (\kappa + \iota)Q_{SC}S_{A/B} \Rightarrow (\kappa + \iota).
\end{equation}

Where, \( S_B = \frac{\lambda_BA_0}{k}T^2e^{-\left(\frac{(1-\eta_\beta)W_\beta}{kT}\right)}Q_{SC} = \beta S_{A/B} Q_{SC} \), and \( S_A = \frac{\lambda_AA_0}{k}e^{-\left(\frac{(1-\eta_\xi)W_\xi}{kT}\right)}Q_{SC} = \beta S_{A/B} Q_{SC} \), which were extracted from the exponential decay \( Q_{SC} \) output. \( \Phi_A \), \( \Phi_B \), and \( \Phi_{A/B} \) are the extracted potential barrier heights from experimental results of metal/polymer A, metal/polymer B, and polymer A/ polymer B, respectively, as referred to Table S2 and Table 1. Therefore, based on Equations (17) and (19) as well as the experimental results, contribution ratios, \( \alpha + \gamma \) and \( \iota \) can be derived respectively. Through the definition, we have

\begin{equation}
J_{A/B} = J_\alpha - J_\beta + J_\gamma + J_\xi - J_\kappa = \alpha J_{A/B} - \beta J_{A/B} + \gamma J_{A/B} + \xi J_{A/B} - \kappa J_{A/B}.
\end{equation}
the net surface charge, possibly due to the existence of the mosaic effect. As demonstrated previously through redox reaction driven by the triboelectric charge, the overall corresponding charge amount for redox reaction was much larger than the net charge measured by Faraday pail. These conclusions indicate that the net charge output from TENG is usually lower than the total triboelectric charge generation, which indicates that there is still large potential in surface charge generation. Therefore, evaluating the charge generation rate based on the material systems becomes necessary to optimize the performance of TENG. The data and details of the calculation for the 6 mechanisms were summarized in Table S3. It should be noticed that the contribution ratios are different for the temperatures above and below the glass transition temperature, probably due to the varied material properties. Due to the calculated values, mass transfer may play an important role in the polymer/polymer. Unfortunately, the accurate contribution ratios by the mass transfer to the real surface charge cannot be identified, as the ratios, $\gamma$ and $\alpha$ in $\gamma + \alpha$, and $\beta$, $\kappa$, and $\iota$ in $\beta + \kappa + \iota$, cannot be distinguished through the thermionic emission behaviors. Therefore, the minimum contribution ratios by mass transfer were evaluated through the ratio $\xi$ over the total negative charge generation ratio $\zeta = \beta + \kappa + \iota$, as summarized in Table 2, indicating that mass transfer is non-negligible in polymer/polymer CE.

To identify the field-effect factors, the CE model was simplified based on different wear rate situations. As demonstrated in previous experiments, when the initial surface charge is induced by the nitrile-butadiene rubber (NBR), little debris remained on the charged surface due to the extremely excellent antiwear property of NBR, and the measured $\Phi$ is affected by the debris of NBR very little. Therefore, because each polymer presents disparate wear rate in scale as shown in Table S4, we can consider only the mass transfer from high-wear-rate polymer to low-wear-rate one, and then, only 4 different mechanisms in Figure 1E remain in the polymer/polymer CE model in each situation, as shown in the simplified CE model in Figure S9. Details of the simplification was summarized in Supporting Information Note S3, where the $\eta_\alpha$ and $\eta_\beta$ and the contribution ratios for different wear-rate situations were derived and results were summarized in Tables S5–S8. Additionally, the different field effect factors for the same polymer may be attributed to the non-uniformly distributed local electric field considering $\eta \propto E$. However, the major factor that impacts the potential barrier height (the factor $\eta$) is the net surface charge. It can be noticed from Figure 3 that when the initial surface charge was enhanced from 90 to 130 nC, $\eta$ of PTFE was enhanced a lot ($\Phi_{\text{PTFE}}$ changed a lot), while the $\eta$ from other pairs with similar net surface charge shows slight change, as shown in Table S8.

To better understand the relationship between the charge generation and the polymer properties, the positive and negative charge generation ratios by different mechanisms were evaluated. By unifying the net charge generation as 1, the negative charge generation ratio, marked as $\zeta$, is defined as $\alpha + \gamma + \xi$. Therefore, the positive charge generation rate should be $\zeta - 1$. Definitions of these parameters were summarized in Table 3.

Previous studies demonstrated that the charge generation was related to the hardness difference between employed polymers, where a larger hardness difference resulted in a larger surface charge density. Considering the evitable mass transfer during polymer/polymer triboelectrification, we hypothesis that wear rate may play an important role considering the correlation between surface hardness and the wear rate because a larger wear rate can easily result in more material transfer as well as the charged mass. Here the relationship between wear rates of polymers and contribution ratios in the bidirectional charge transfer process was evaluated and summarized in Figure 4. With the FEP considered as the reference, wear-resistant abilities of different polymers were sorted and shown in Figure S8, where the ratio in wear rates between FEP and each polymer is considered as the relative wear rate as shown in Table S4 and illustrated in Figure 4A. The corresponding charge generation rate of surface charge for each polymer pair under part II (above the glass transition temperature) was plotted in Figure 4B. Here, the wear rate ratio of polymer pair A/B, $\chi$, was defined as the ratio of the larger wear rate over the smaller one, and the sign of charge generation rate in Figure 4B was employed to illustrate the polarity of surface charge. From Figure 4B, it can be noticed that a higher $\chi$ was prone to result in larger charge generation rates with both polarities under each part, indicating that much more surface charges were generated during the total charge transfer process (from both mass and electron transfers).
Although higher relative wear rate possibly results in larger charge generation rate, the mosaic surface with sufficient surface charges also widely exists in polymer pairs with low relative wear rate, as shown by Kapton/PCII and PTFEII/FEPII. These results demonstrated that the charge generation may be closely related to the wear rate ratio, indicating that mass transfer is non-negligible in polymer/polymer CE.

Based on the derivations of charge decay rate $S_A$, $S_B$, and $S_{A/B}$, the contribution ratios can also be roughly reflected by the corresponding potential barrier difference, where the derivations were summarized in Supporting Information Note S4. Thus, potential barrier difference $\Delta \Phi$ was calculated based on Table 1 and Table S2 to illustrate the relationship among $\Phi_A$, $\Phi_B$, and $\Phi_{A/B}$, as shown in Figure 4C. Here:

$$\Delta \Phi_A = \Phi_{A/B} - \Phi_A.$$  \hspace{1cm} (22)

And,

$$\Delta \Phi_B = \Phi_{A/B} - \Phi_B.$$  \hspace{1cm} (23)

As shown in Figure 4C as well as the measured $\Phi$ in Figure S4, the $\Phi_{A/B}$ was either smaller than both $\Phi_A$ and $\Phi_B$ or between the two, and the relative potential barrier differences, $\Delta \Phi_A$ and $\Delta \Phi_B$, are usually not close to 0, indicating the thermionic emission contributions from both materials A and B, which verifies the existence of mass transfer along with electron transfer. As compared in Figure 4B,C, a larger $\Delta \Phi_A$ or $\Delta \Phi_B$ may be obtained along with larger charge generation ratios, which indicates the charge generation contributions from the mass transfer. However, because the contribution ratios of different charge transfer mechanisms were highly related to the properties of employed polymers and the interactions between the surfaces, counterexamples can be found, such as the Kapton/PCII. The relationship between the wear rate ratios and the charge generation ratios under different wear rate situations was investigated as well, as discussed in Supporting Information Note S5, Figures S9–S10 and Table S9, where similar tendency can be observed, further confirming that inevitable of the mass transfer in polymer/polymer CE.

### TABLE 3 Definition summary of different parameters

| Term | Definition |
|------|------------|
| $W$  | potential barrier height at the thermodynamic equilibrium (when the applied voltage equals to 0) |
| $J$  | Overall current density by the thermionic emission |
| $A_0$ | Richardson constant of free electrons |
| $k$  | Boltzmann constant |
| $\alpha$ | Contribution ratio of electrons transfer from A to B |
| $\beta$ | Contribution ratio of negatively charged mass transfer from B to A |
| $\gamma$ | Contribution ratio of positively charged mass transfers from B to A |
| $\xi$ | Contribution ratio of negatively charged mass transfer from A to B |
| $\iota$ | Contribution ratio of electrons transfer from B to A. |
| $\kappa$ | Contribution ratio of negatively charged mass transfer from A to B |
| $\eta$ | Electric field factor on the potential barrier height change |
| $\Phi$ | Measured potential barrier height |
| $\zeta_A$ | The negative charge generation ratio, defined as the sum of $(\alpha + \xi)$ for situation that the wear rate of A is larger than that of B |
| $\zeta_B$ | The negative charge generation ratio, defined as the sum of $(\alpha + \gamma)$ for situation that the wear rate of B is larger than that of A. |
| $\chi$ | Relative wear rate of polymer pair A/B, defined as the ratio of the larger wear rate over the smaller one |
| $\Delta \Phi_A$ | Relative potential barrier height change between $\Phi_A$ and $\Phi_{A/B}$, $(\Phi_{A/B} - \Phi_A)$ |
| $\Delta \Phi_B$ | Relative potential barrier height change between $\Phi_B$ and $\Phi_{A/B}$, $(\Phi_{A/B} - \Phi_B)$ |

### 4 DISCUSSION

In summary, a quantified model was proposed to investigate the CE, with the contribution ratios from different charge transfer mechanisms identified for different polymers. Based on Richardson’s law, the potential barrier height $\Phi$ of different polymer/polymer pairs were extracted from the thermionic emission behaviors. Since $\Phi$ is affected by the electric field, different charge transfer
mechanisms can be distinguished by the polarity of the charge transfer and the corresponding emission materials.

Considering the random breakage of chemical bonds of both surfaces, the transferred materials may include both positive and negative charges. Additionally, considering the different electron affinities of local atoms in molecular chain, the electron transfer was also bidirectional, and thus the polymer/polymer CE model with six potential mechanisms was established. A quantified model for calculating the contribution ratios of different charge transfer mechanisms was thus derived, and the contribution ratios were calculated. These contribution ratios were usually larger than 1, indicating that the total generated charge in CE is actually much larger than the net surface charge, which is also consistent with the previous studies. The relationship between the positive/negative

**FIGURE 4** Relationship between wear rates of polymers and contribution ratios. (A) Wear rate difference of different polymer pairs without simplification. (B) The charge generation rate of surface charge with different polarities of different polymer pairs without simplification. (C) Potential barrier difference for illustrating the relationship among $\Phi_A$, $\Phi_B$, and $\Phi_{A/B}$. Here, polymer pairs under part II were investigated.

**TABLE 4** Summary for charge generation rate

| Material pairs       | $\chi$  | $\alpha+\gamma+\zeta$ | $\beta+\kappa+\iota$ | $\Delta\Phi_A$ (eV) | $\Delta\Phi_B$ (eV) |
|----------------------|---------|------------------------|-----------------------|---------------------|---------------------|
| PC$_I$/PTFE$_I$      | 178.7   | -6.995                 | 5.995                 | 0.171529            | -0.18539            |
| Kapton/PTFE$_I$      | 74.4    | -1.8581                | 0.8581                | -0.63271            | -0.45931            |
| Kapton/PC$_I$        | 0.41667 | -14.0735               | 13.0735               | -0.09777            | 0.1359              |
| PEEK$_I$/PC$_I$      | 19.76285| -7.8557                | 6.8557                | -0.28187            | 0.24835             |
| PC$_II$/PTFE$_II$    | 178.7   | -9.8336                | 8.8336                | -0.10866            | 0.90799             |
| PC$_II$/FEP$_II$     | 178.7   | -7.9238                | 6.9238                | -0.68396            | 0.43009             |
| Kapton/PTFE$_II$     | 74.44444| -7.3676                | 6.3676                | -0.07088            | 0.10246             |
| Kapton/FEP$_II$      | 74.44444| -3.6616                | 2.6616                | -0.50426            | -0.23396            |
| PEEK$_II$/PC$_II$    | 19.76285| -3.7765                | 2.7765                | -0.01865            | 0.4749              |
| Kapton/PC$_II$       | 2.4     | -4.3195                | 3.3195                | 0.51506             | -0.32867            |
| PTFE$_II$/FEP$_II$   | 1       | -3.696                 | 2.696                 | -0.15108            | -0.05403            |

| Material pairs       | $\chi$  | $\alpha+\gamma+\zeta$ | $\beta+\kappa+\iota$ | $\Delta\Phi_A$ (eV) | $\Delta\Phi_B$ (eV) |
|----------------------|---------|------------------------|-----------------------|---------------------|---------------------|
| PC$_I$/PTFE$_I$      | 178.7   | -6.995                 | 5.995                 | 0.171529            | -0.18539            |
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| PTFE$_II$/FEP$_II$   | 1       | -3.696                 | 2.696                 | -0.15108            | -0.05403            |
charge generation ratio and the relative wear rate ratio, as well as the relationship between the relative potential barrier height and the relative wear rate ratio were investigated, further confirming the material-dependent CE mechanism in polymer/polymer CE. This study demonstrated the field-assisted thermionic emission method toward achieving a quantitative model for CE mechanisms in polymer/polymer triboelectric pairs with the contribution ratio of each charge transfer mechanism confirmed, which may contribute to understand the millennium puzzle in tribo electrification and provides a new perspective for promoting applications related to the surface charge tailoring.

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CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available in the supplementary material of this article.

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REFERENCES
1. Zhu G, Pan C, Guo W, et al. Triboelectric-generator-driven pulse electrodeposition for micropatterning. Nano Lett. 2012;12(9):4960-4965.
2. Liu G, Nie J, Han C, et al. Self-powered electrostatic adsorption face mask based on a triboelectric nanogenerator. ACS Appl Mater Interfaces. 2018;10(8):7126-7133.
3. Wang S, Lin L, Wang ZL. Nanoscale triboelectric-effect-enabled energy conversion for sustainably powering portable electronics. Nano Lett. 2012;12(12):6339-6346.
4. Chen J, Wang ZL. Reviving vibration energy harvesting and self-powered sensing by a triboelectric nanogenerator. Joule. 2017;1(3):480-521.
5. Wu C, Wang AC, Ding W, Guo H, Wang ZL. Triboelectric nanogenerator: a foundation of the energy for the new era. Adv Energy Mater. 2019;9(1):1802906.
6. Wang ZL. Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors. ACS Nano. 2013;7(11):9533-9557.
7. Wang ZL. On Maxwell's displacement current for energy and sensors: the origin of nanogenerators. Mater Today. 2017;20(2):74-82.
8. Li X, Xu G, Xia X, Fu J, Huang L, Zi Y. Standardization of triboelectric nanogenerators: progress and perspectives. Nano Energy. 2019;56:40-55.
9. Niu S, Wang ZL. Theoretical systems of triboelectric nanogenerators. Nano Energy. 2015;14:161-192.
10. Niu S, Wang S, Lin L, et al. Theoretical study of contact-mode triboelectric nanogenerators as an effective power source. Energy Environ Sci. 2013;6(12):3576-3583.
11. Niu S, Liu Y, Wang S, et al. Theory of sliding-mode triboelectric nanogenerators. Adv Mater. 2013;25(43):6184-6193.
12. Niu S, Liu Y, Chen X, et al. Theory of freestanding triboelectric-layer-based nanogenerators. Nano Energy. 2015;12:760-774.
13. Lebedev M, Akedo J. What thickness of the piezoelectric layer with high breakdown voltage is required for the micro-actuator? Jpn J Appl Phys. 2002;41:3344-3347.
14. Wang J, Wu C, Dai Y, et al. Achieving ultrahigh triboelectric charge density for efficient energy harvesting. Nat Commun. 2017;8(1):38.
15. Luo J, Xu L, Tang W, et al. Direct-current triboelectric nanogenerator realized by air breakdown induced ionized air channel. Adv Energy Mater. 2018;8(27):1800889.
16. Zi Y, Wu C, Ding W, Wang ZL. Maximized effective energy output of contact-separation-triggered triboelectric nanogenerators as limited by air breakdown. Adv Funct Mater. 2017;27(24):1700049.
17. Hu W, Wei X, Zhu L, et al. Enhancing proliferation and migration of fibroblast cells by electric stimulation based on triboelectric nanogenerator. Nano Energy. 2019;57:600-607.
18. Zhou YS, Wang S, Yang Y, et al. Manipulating nanoscale contact electrification by an applied electric field. Nano Lett. 2014;14(3):1567-1572.
19. Jin L, Xiao X, Deng W, et al. Manipulating relative permittivity for high-performance wearable triboelectric nanogenerators. Nano Lett. 2020;20(9):6404-6411.
20. Xia X, Wang H, Guo H, Xu C, Zi Y. On the material-dependent charge transfer mechanism of the contact electrification. Nano Energy. 2020;78:105343.
21. Crowell CR. The Richardson constant for thermionic emission in Schottky barrier diodes. Solid-State Electron. 1965;8(4):395-399.
22. Xu C, Wang AC, Zou H, et al. Raising the working temperature of a triboelectric nanogenerator by quenching down electron thermionic emission in contact-electrification. Adv Mater. 2018;30(38):e1803968.
23. Liu CY, Bard AJ. Chemical redox reactions induced by cryptoelectrons on a PMMA surface. J Am Chem Soc. 2009;131(18):6397-6401.
24. Xu C, Zi Y, Wang AC, et al. On the electron-transfer mechanism in the contact-electrification effect. Adv Mater. 2018;30(15):e1706790.
25. Lin S, Xu L, Xu C, et al. Electron transfer in nanoscale contact electrification: effect of temperature in the metal-dielectric case. Adv Mater. 2019;31(17):e1808197.
26. Wiles JA, Fialkowski M, Radowksi MR, Whitesides GM, Grzybowski BA. Effects of surface modification and moisture on the rates of charge transfer between metals and organic materials. J Phys Chem B. 2004;108(52):20296-20302.
27. McCarty LS, Whitesides GM. Electrostatic charging due to separation of ions at interfaces: contact electrification of ionic electrets. Angew Chem Int Ed Engl. 2008;47(12):2188-2207.
28. Wiles JA, Grzybowski BA, Winkleman A, Whitesides GM. A tool for studying contact electrification in systems comprising metals and insulating polymers. Anal Chem. 2003;75(18):4859-4867.
29. Thomas SW, Vella SJ, Kaufman GK, Whitesides GM. Patterns of electrostatic charge and discharge in contact electrification. Angew Chem Int Ed Engl. 2008;120(35):6756-6758.

30. Vella SJ, Chen X, Thomas SW, Zhao X, Suo Z, Whitesides GM. The determination of the location of contact electrification-induced discharge events. J Phys Chem C. 2010;114(48):20885-20895.

31. Pezzotti G, Camara C, Marin E, et al. Physical chemistry insights into surface charge phenomena during frictional coupling in triboelectric X-ray sources. J Mater Chem C. 2019;7(25):7708-7724.

32. Baytekin HT, Patashinski AZ, Branicki M, Baytekin B, Soh S, Grzybowski BA. The mosaic of surface charge in contact electrification. Science. 2011;333(6040):308-312.

33. Vincent G, Chantre A, Bois D. Electric field effect on the thermal emission of traps in semiconductor junctions. J Appl Phys. 1979;50(8):5484-5487.

34. Greffet J-J, Carminati R, Joulain K, Mulet J, P, Mainguy S, Chen Y. Coherent emission of light by thermal sources. Nature. 2002;416(6876):61-64.

35. Zi Y, Wu C, Ding W, et al. Field emission of electrons powered by a triboelectric nanogenerator. Adv Funct Mater. 2018;28(21):1800610.

36. Sherrill PC, Sutka A, Shepelin NA, et al. Probing contact electrification: a cohesively sticky problem. ACS Appl Mater Interfaces. 2021;13(37):44935-44947.

37. Xia X, Fu J, Zi Y. A universal standardized method for output capability assessment of nanogenerators. Nat Commun. 2019;10(1):4428.

38. Burgo TA, Ducati TR, Francisco KR, Clinckspoor KJ, Galembeck F, Galembeck SE. Triboelectricity: macroscopic charge patterns formed by self-arraying ions on polymer surfaces. Langmuir. 2012;28(19):7407-7416.

39. Zhang J, Rogers FJM, Darwish N, et al. Electrochemistry on tribocharged polymers is governed by the stability of surface charges rather than charging magnitude. J Am Chem Soc. 2019;141(14):5863-5870.

40. Šutka A, Málniškis K, Lapčinskis L, et al. The role of intermolecular forces in contact electrification on polymer surfaces and triboelectric nanogenerators. Energy Environ Sci. 2019;12(8):2417-2421.

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SUPPORTING INFORMATION

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