Thermally driven single-electron stochastic resonance

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Abstract

Stochastic resonance (SR) in a single-electron system is expected to allow information to be correctly carried and processed by single electrons in the presence of thermal fluctuations. Here, we comprehensively study thermally driven single-electron SR. The response of the system to a weak voltage signal is formulated by considering the single-electron tunneling rate, instead of the Kramers’ rate generally used in conventional SR models. The model indicates that the response of the system is maximized at finite temperature and that the peak position is determined by the charging energy. This model quantitatively reproduces the results of a single-electron device simulator. Single-electron SR is also demonstrated using a GaAs-based single-electron system that integrates a quantum dot and a high-sensitivity charge detector. The developed model will contribute to our understanding of single-electron SR and will facilitate accurate prediction, design, and control of single-electron systems.

Keywords: single electron, stochastic resonance, thermal fluctuation, GaAs nanowire, theoretical model, nonlinear

(Some figures may appear in colour only in the online journal)

1. Introduction

Single-electron electronics, in which an elementary particle carries information, has been investigated since the 1980s with the goal of ultra-low-power computing [1–8]. However, single-electron devices are quite sensitive to thermal fluctuations characterized by \( k_B T \) (\( k_B \) is the Boltzmann constant) and lose information at finite temperature [9–11]. Thermal fluctuations can easily flip bits and thus cannot be allowed in the conventional digital computing systems. A straightforward way to overcome this problem is to make the charging energy \( E_C \) larger than the thermal energy by reducing the quantum dot (QD) size [11]. However, the variation in device characteristics is increased by reducing the size, because it is difficult to maintain size uniformity on the nanoscale. Another way of dealing with thermal fluctuations is to cause stochastic resonance (SR) in single-electron systems [12–14].

SR is a phenomenon in which the response of a system to a weak signal is enhanced by the addition of noise [15, 16]. SR occurs in diverse systems, including biological ones (e.g. humans) [17–22]. It is known that SR arises in a threshold or bistable system. SR using thermal fluctuations as noise has been demonstrated in a nanoscale device [23] and a superconducting device [24]. In particular, it is expected to arise in a single-electron system under thermal fluctuations. Single-electron SR was first shown in numerical simulations [12, 13]. Later, it was experimentally demonstrated at room temperature using sophisticated silicon nanodevice technology and its application to image sensing was presented [14]. Moreover, an experimental...
The single-electron system is schematically shown in figure 1(a) and its equivalent circuit is shown in figure 1(b). The configuration of the system follows that of previous experimental studies [14, 25–29]. The system consists of a QD connected to an input lead through a tunnel barrier. Single-electron charging and discharging of the QD is carried out by applying a voltage signal V_in to the input lead. The nanowire FET nearby the QD is capacitively coupled with the QD and the charge state of the QD can be detected in real time from the change in the drain current I_ds.

When the charge response of the QD to V_in in this system is maximized at finite temperature, this is referred to as thermally driven single-electron SR. The charge state in the QD is discretized when the charging energy E_C caused by the Coulomb interaction between individual electrons is large, and thus a small V_in (<E_C/e) cannot change the charge in the QD at 0 K (the so-called Coulomb blockade). When the temperature rises, a small V_in can overcome the Coulomb blockade with the help of thermal energy, k_B T, and then electron charging and discharging of the QD occurs through the tunnel barrier. By increasing the temperature further, charging and discharging occur frequently regardless of the value of V_in and the correlation between the charge in the QD and V_in is lost.

In order to formulate the above behavior, we note that the stochastic single-electron dynamics can be described by means of the average frequency of oscillatory single-electron charging and discharging of the QD, f. This frequency corresponds to that of pulses in the current through the charge detector. Here, the single-electron tunneling rate is exactly incorporated into the formulation [30, 31]. In general, models of SR usually use the Kramers’ rate developed for noise-assisted transitions [16, 32–35]. On the other hand, a recent study on SR in a bistable system indicated that the description of the transition rate has a critical impact on SR behavior [36]. The single-electron charging rate \( \Gamma_+ \) and discharging rate \( \Gamma_- \) for a QD through a tunnel barrier are given by [31]

\[
\Gamma_\pm = \mp \frac{1}{e^2 R_T} \frac{(E_C + eV)}{1 - \exp \left( \pm \frac{E_C + eV}{k_B T} \right)},
\]

where \( V = C_T e V_{in}/(C_T + C_N) \) is the voltage drop across the tunnel capacitance and \( R_T \) is the tunnel resistance. The average charging and discharging times, \( \langle \tau_+ \rangle \) and \( \langle \tau_- \rangle \), respectively, are given by the inverse of the mean single-electron tunneling rates, \( \langle \tau_+ \rangle = 1/\Gamma_+ \) and \( \langle \tau_- \rangle = 1/\Gamma_- \).

From equation (1), we immediately obtain the relationship between the time constants as

\[
\frac{\Gamma_-}{\Gamma_+} = \frac{\langle \tau_+ \rangle}{\langle \tau_- \rangle} = \exp \left( \frac{E_C + eV}{k_B T} \right),
\]

corresponding to the principle of detailed balance. It should be noted that the charging energy is involved in the balance.

The frequency of single-electron charge flipping, \( f \), is evaluated as

\[
f = \frac{1}{\langle \tau_+ \rangle + \langle \tau_- \rangle} = \frac{E_C + eV}{2e^2 R_T \sinh \left( \frac{E_C + eV}{2k_B T} \right)} \approx \frac{k_B T}{2e^2 R_T} \left[ 1 - \frac{1}{6 \left( \frac{E_C + eV}{k_B T} \right)^2} \right].
\]

The frequency-voltage curve has a peak. The system often has
multiple states and shows multiple peaks, expressed as
\[
f = \sum \frac{nE_C + eV}{2e^2R_s \sinh\left(\frac{nE_C + eV}{k_B T}\right)}.
\]

The response of the system to the applied voltage is measured by counting pulses in the output of the charge detector, as shown in figure 1(a). The frequency of the current pulse in the detector output corresponds to \(f\). The pulse filling factor \(p\) (percentage of output filled by pulses) can be evaluated from the charging and discharging times as
\[
p = \frac{\langle \tau_\text{c} \rangle}{\langle \tau_\text{c} \rangle + \langle \tau_\text{d} \rangle} = \frac{1}{1 + \langle \tau_\text{d} \rangle / \langle \tau_\text{c} \rangle} = \frac{1}{1 + \exp\left(\frac{E_C + eV}{k_B T}\right)}.
\]

Here, the covariance between the input voltage and the output pulse train, which is the numerator of the correlation coefficient, is evaluated as
\[
C_0 = \frac{1}{T_p} \int_0^{T_p} \langle I_{\text{ds}}(t) \rangle \cdot \langle V_{\text{in}}(t) \rangle dt,
\]
where \(<\>\) denotes the time average. For a square input with period \(T_p\) and a duty ratio of 50%, \(C_0\) is given by
\[
C_0 = \frac{1}{T_p} \left[ \frac{V_a}{2} \int_0^{T_p/2} \langle I_{\text{ds}}^{\text{ON}}(t) \rangle \cdot \langle I_{\text{ds}}(t) \rangle dt \right.
- \left. \frac{V_a}{2} \int_{T_p/2}^{T_p} \langle I_{\text{ds}}^{\text{OFF}}(t) \rangle \cdot \langle I_{\text{ds}}(t) \rangle dt \right],
\]
where
\[
\langle I_{\text{ds}}(t) \rangle = \frac{1}{T_p} \left\{ \int_0^{T_p/2} h \cdot p^{\text{ON}} dt + \int_{T_p/2}^{T_p} h \cdot p^{\text{OFF}} dt \right\}.
\]

The superscripts ON and OFF denote low and high levels of the square wave input, respectively, and \(h\) is the pulse height in the output. Note that
\[
\int_0^{T_p} I_{\text{ds}}^{\text{ON}}(t) dt = \sum_i h \cdot \tau^{\text{ON}}[i] = N^{\text{ON}} \cdot h \cdot \langle \tau^{\text{ON}} \rangle
= \frac{T_p}{\langle \tau^{\text{ON}} \rangle} \cdot h \cdot \langle \tau^{\text{ON}} \rangle = \frac{T_p}{2} h p^{\text{ON}},
\]
where \(p^{\text{ON}}\) is the number of pulses when the input is ‘ON’. Then, the following equation is obtained for the covariance
\[
C_0 = \frac{1}{T_p} \left[ \frac{V_a}{2} \cdot \frac{T_p}{2} \left\{ h p^{\text{ON}} - \frac{h}{2} (p^{\text{ON}} + p^{\text{OFF}}) \right\} \right.
- \left. \frac{V_a}{2} \cdot \frac{T_p}{2} \left\{ h p^{\text{OFF}} - \frac{h}{2} (p^{\text{ON}} + p^{\text{OFF}}) \right\} \right],
\]
\[
= \frac{V_a h}{4} (p^{\text{ON}} - p^{\text{OFF}}).
\]

Substituting \(p\) from equation (5) into the above equation and assuming \(V_{\text{in}} \ll E_C\) and \(k_B T\) yields
\[
C_0 \approx \frac{V_a h}{4} \left(1 + \exp \left(\frac{E_C + eV}{k_B T}\right)\right) - \frac{1}{1 + \exp \left(\frac{E_C + eV}{k_B T}\right)}.
\]
In addition, by considering equations (1) and (2), \( R_{\text{f}} \) reduces the effect of thermal energy on the electron transition response. On the other hand, the effect of low temperatures allows a few electrons to contribute to the output, and the total tunnel resistance dependence. Similar to the case of large \( R_{\text{f}} \) total, the peak becomes larger than in the low regime. Note as well that our model deals with classical single-electron behavior; it thus does not incorporate relatively small quantum fluctuations. Recent sophisticated quantum device technology has enabled observation of another class of single-electron SR by using quantum fluctuations that assist the single-electron transition even at very low temperatures [40].

3. Experimental demonstration

An experimental demonstration of the single-electron SR system was carried out by implementing it using a Schottky gate-controlled GaAs T-shaped nanowire junction (figure 1(c)). The nanowire was fabricated on a standard AlGaAs/GaAs heterostructure on a (001) semi-insulating GaAs substrate having two-dimensional electrons by using electron-beam lithography and chemical etching [41–43]. A QD was electrostatically formed in the nanowire between gates 1 and 2. The voltage applied to gate 1 on the input lead side was adjusted to form a tunnel capacitance \( C_{\text{T}} \), and the voltage applied to gate 2 was adjusted to electrically isolate the QD from the charge detector FET but to couple them capacitively with a normal capacitance \( C_{\text{N}} \). \( C_{\text{total}} \) was estimated to be 21 aF from the fabricated device dimensions and dc characteristics. This capacitance corresponds to a charging energy of 3.8 mV (44 K). In a previous study of single-electron SR, the fluctuation of the electrons was electrostatically changed [14]. In contrast, the fluctuation in this study was controlled by changing the environmental temperature. The measurements were carried out using a low-temperature probe station. The environmental temperature was varied from 8 to 100 K.

First, single-electron charging and discharging together with their detection were examined. Figure 3(a) shows the measured \( I_{\text{ds}} \) for several constant values of \( V_{\text{in}} \) at 8 K. For convenience, the figure plots \( -I_{\text{ds}} \), in which a pulse appears when an electron is added to the QD. A pulse train appears in \( I_{\text{ds}} \); the frequency of the pulse train depends on \( V_{\text{in}} \). The voltage drop across the tunnel barrier is given by \( V = V_{\text{in}}C_{\text{N}}/(C_{\text{T}} + C_{\text{N}}) \). It was found that \( V \sim V_{\text{in}}/3 \) from \( C_{\text{N}} \sim C_{\text{T}}/2 \). A relatively thick potential barrier formed beneath gate 2 and prevented electron tunneling.

To quantitatively see the input voltage dependence of the output pulse, we evaluated the average pulse generation frequency \( f \). The result is shown in figure 3(b). The plots indicate that the frequency of charging and discharging was modulated by \( V_{\text{av}} \). \( f \) itself oscillated with a further increase or decrease in \( V_{\text{in}} \). The oscillation period for \( V_{\text{in}} \) was 10.5 mV, corresponding to 3.5 mV for \( V \). This value is reasonably close to \( E_{\text{C}}/e \approx 3.8 \text{ mV} \). Therefore, the oscillation of \( f \) was attributed to the increment/decrement of single electrons in the QD. The mechanism of oscillation is shown in figure 3(c). As the potential of the input lead is increased, an electron enters the QD from the input lead. When the electron is added to the QD, the electrochemical potential in the QD simultaneously increases by \( E_{\text{C}} \), promoting discharging. Such charging and discharging repeatedly occur even with a constant input. When the input voltage is increased further, the system is stabilized with the added electron and pulse generation is inhibited. Thus, the oscillation of \( f \) in figure 3(b) is analogous to Coulomb oscillation [30, 44]. As indicated by the
Figure 3. Charging and discharging behavior of QD under dc input voltage. (a) Measured $I_{\text{ds}}$ in the time domain. (b) Evaluated pulse frequency as a function of $V_{\text{in}}$ at 8 K. (c) Schematic energy diagram and charge dynamics of system in QD. I: negative voltage below $E_{\text{C}}/e$ is applied to system. II: further decrease in voltage. III: system reaches next stable state.

solid lines in figure 3(b), this oscillation is reproduced by equation (4), assuming $R_T = 10^{14} \Omega$.

The pulse generation was rather prominent at $V_{\text{in}} = -10$ mV in figure 3(a), and a discrepancy was observed between experiment and theory at large negative voltages as shown in figure 3(b). From equation (3), these behaviors can be understood by the decrease in the charging energy and/or the tunnel resistance at large negative voltage. The variations in the device parameters were possibly caused by unintentional structural and/or electrostatic non-uniformity in the device. There was also a possibility of external fluctuations other than thermal ones. To remove the observed variations in the behavior, precise control of the device and the environment would be necessary.

Figure 4(a) shows the temperature dependence of the response to a time series signal. Hereafter, the input ‘ON’ refers to the voltage level for charging the QD and ‘OFF’ refers to that for discharging. At 9 K, the output was almost asynchronous to the input. As the temperature increased, more pulses were generated, and the output started to follow the input. With a further increase in temperature, many pulses appeared regardless of the input voltage. The charge response of the QD to the input was quantitatively measured using the correlation coefficient $C_i$ between the input voltage and the drain current, defined as

$$C_i = \frac{\langle V_{\text{in}}(t) \cdot I_{\text{ds}}(t) \rangle - \langle V_{\text{in}}(t) \rangle \cdot \langle I_{\text{ds}}(t) \rangle}{\sqrt{\langle V_{\text{in}}^2(t) \rangle - \langle V_{\text{in}}(t) \rangle^2} \cdot \sqrt{\langle I_{\text{ds}}^2(t) \rangle - \langle I_{\text{ds}}(t) \rangle^2}}.$$  \hspace{1cm} (13)

Figure 4(b) shows the evaluated correlation coefficients as a function of temperature at $eV = 0.5E_{\text{C}}$ and $0.15E_{\text{C}}$. Each curve has a peak at around 20 K, indicating that the response was optimized at a non-zero temperature. This behavior confirms that SR occurred in our system. A larger input amplitude resulted in a larger $C_i$. The peak value of $C_i$ was 0.3 at $eV = 0.5E_{\text{C}}$. The position of the peak was approximately half of the charging energy for both curves and it was not affected by the voltage on the tunneling barrier. The experimental behavior could be quantitatively matched the theoretical curves derived from equations (5) and (12). The only parameters required for the computation of the theoretical curves were $E_{\text{C}}$ and $V_{\text{in}}$: no empirical parameter was used in our model.

The covariance $C_0$ was analyzed to better understand what determines the response peak. $C_0$ is the numerator of $C_i$ and is proportional to $p_{\text{ON}} - p_{\text{OFF}}$, as indicated in equation (9). Assuming that $V$ is smaller than $k_BT$ and $E_{\text{C}}$, the temperature that maximizes the response is approximately $E_{\text{C}}/2k_B$. This temperature can explain the position of the peak in the responses shown in figure 4(b). Thus, the charging energy is significantly involved in the response. On the other hand, equation (9) suggests that $R_T$ is not involved in the response, because the response is determined by the ratio of the charging and discharging times, in which $R_T$ is canceled out. In addition, by considering equations (9), (10), and (12), it is found that the input-output correlation coefficient linearly depends on the amplitude of the input voltage. Therefore, the
applied voltage affected the response peak height, but it did not affect the peak position.

4. Discussion

We examined the single-electron dynamics involved in SR by characterizing the time series of the charge dynamics in the fabricated system. First, we verified the charging and discharging of the QD by electrons one by one. Figure 5(a) shows a histogram of pulse edge intervals \( \Delta t \) at 8 K obtained from the time series of \( I_{ds} \). \( \Delta t \) corresponds to the timing that a charge entered the QD. The distribution of the chargings follows a Poisson distribution, indicating that the discrete events randomly occurred in this system [29]. Considering the capacitive coupling \( C_N \) of 7 aF between the charge detector and the QD (\( C_N + C_T = 21 \) aF and \( C_N \sim C_T/2 \)) together with the measured transconductance of 20 \( \mu \)S in the charge detector, the change in \( I_{ds} \) due to adding an electron to the QD was estimated to be 32 nA. This value reasonably corresponded to the observed pulse height in \( I_{ds} \), around 20 nA.

Next, we identified the transition process between tunneling and thermal activation. The temperature dependences of the average charging and discharging times, \( \langle \tau_+ \rangle \) and \( \langle \tau_- \rangle \), were characterized at \( V_{in} = 0 \) V. The charging time \( \tau_+ \) corresponds to the waiting time for adding an electron to the QD, which is
given by the interval between pulses in the time series of $-I_d$. Similarly, the discharging time $\tau_d$ corresponds to the waiting time for discharging an electron from the QD, which is given by the pulse width. $\langle \tau_s \rangle$ and $\langle \tau_d \rangle$ were evaluated by counting all intervals or pulse widths in the time series of $-I_d$ and averaging them. As shown in figure 5(b), at low temperatures, charging took much longer than discharging. The charging time decreased rapidly as the temperature increased, approaching the discharging time, which resulted in an increase in $f$, as schematically shown in figure 5(c). The experimentally observed behavior follows the single-electron tunneling of equation (1), assuming a small offset of the input voltage (solid lines in figure 5(b)). The unintentional offset was probably caused by the background charge. At low temperature, the discharging time remained around 2 s, whereas the charging time increased. This result indicated that the state transition involved the tunneling process. From the discussion above, we conclude that the relevant mechanism behind the observed thermally driven charge dynamics in our system was single-electron tunneling.

As indicated by equation (12), the correlation between the input and output is related to the single-electron charging and discharging times through the pulse filling factor $p$, defined as $p = \langle \tau_s \rangle/(\langle \tau_s \rangle + \langle \tau_d \rangle)$. The $p$ value calculated from the experimental data was consistent with the theoretical curve obtained from equations (2) and (5). It should be mentioned that the state transition and SR in a system controlled by single-electron tunneling is clearly distinguished from those with the conventional Arrhenius type of thermal activation, where $\langle \tau \rangle = \tau_0 \exp(\Delta \varphi/k_B T)$ and $\Delta \varphi$ is potential barrier height. In the conventional SR system, the position of the peak response is controlled by $\Delta \varphi$ [16], whereas $p$ and the detailed balance are determined by the energy difference between the two states, not by $\Delta \varphi$ [45]. On the other hand, in the single-electron system, the SR peak position $p$ and the detailed balance are controlled by $E_C$.

The analysis on the single-electron system also suggests that the peak of $C_1$ for the weak signal of $|eV| < E_C/2$ is essentially limited to $1/3^{0.5}$ at maximum, because the theoretical maximum value of $p$ is 0.5, from equations (2) and (5). For further improvement of the response, it is necessary to overcome this limit. Biological systems achieve this by introducing redundancy; they are known to improve the SR response by using a summing network [46]. A numerical simulation showed that this approach is feasible in single-electron systems [12, 13]. In the context of our model, the pulse filling factor for an $N$-device network is considered to be $Np$, because the pulse timings in the devices are uncorrelated. As a result, $C_1$ for the $N$-device network is approximately given by $\sqrt[N]{NC_1}$, indicating an improvement in the response by a factor of $\sqrt[N]{N}$.

Finally, the value of the observed response peak would have been underestimated because the output was an encoded signal in terms of information transfer; the amplitude of the input signal was encoded in the pulse frequency, as shown in figure 3(a), as in frequency modulation. Accordingly, by using an appropriate decoding process, the input signal should be able to be recovered from the output pulse train, resulting in a larger $C_1$ [47].

5. Conclusion

Thermally driven single-electron SR was comprehensively investigated through modeling, simulation, and experiments. The formulation of the response of the system to a weak voltage signal took into account single-electron tunneling. It was found that the input-output correlation was maximized at a temperature determined by the charging energy of the system. The model quantitatively reproduced the results obtained from a single-electron device simulator. Single-electron SR was experimentally demonstrated using a GaAs-based single-electron system that integrated a high-sensitivity charge detector. We found that the behaviors of the single-electron tunneling were different from those in SR with Arrhenius-type thermal activation. The observed behavior could be quantitatively explained by the developed model. The results obtained in this study will contribute to our understanding of single-electron SR and will facilitate the accurate prediction, design, and control of systems for unconventional computing using single electrons.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Financial interest

The authors declare no competing financial interests.

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