Spin Seebeck Effect in a Hybridized Quantum-Dot/Majorana-Nanowire With Spin Heat Accumulation

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Properties of spin Seebeck effect (SSE) in a quantum dot (QD) connected to a topological superconductor or semiconductor nanowire with strong spin-orbit interaction are theoretically studied by the nonequilibrium Green’s function method combined with Dyson equation technique. At low temperatures, Majorana zero modes (MZMs) are prepared at the ends of topological superconductor or semiconductor nanowire, and are hybridized to the QD with spin-dependent strength. We consider that the QD is coupled to two leads in the presence of spin heat accumulation (SHA), i.e., spin-dependent temperature in the leads. We find that the thermopower is spin-polarized when the hybridization strength between the QD and one mode of the MZMs depends on electron spin direction, and its spin-polarization can be effectively adjusted by changing the magnitude of SHA. By proper variation of the spin-polarization of the QD-MZM hybridization strength, magnitude of the SHA, dot level, or the direct coupling between the MZMs, 100% spin-polarized or pure thermopower can be generated. Our results may find real usage in high efficiency spintronic devices or detection of the MZMs, which are under current extensive study. The present model is within the reach of current nano-technologies and may be used in high efficiency spin caloritronics devices.

Keywords: spin-dependent temperature, quantum dot, Majorana zero modes, spin seebeck effect, spin-polarized coupling

1 INTRODUCTION

In the last decades, generating and manipulating spin current in closed circuits or spin bias in open ones by thermal bias have been successfully realized in experiments. This interdisciplinary subject of thermoelectric effect and spintronics is referred to as spin caloritronics aiming at spin control in terms of thermal means [1, 2]. In the usual thermoelectric effect, the Seebeck effect known as generation of electrical current or bias voltage in response to a temperature difference between two ends of a system is the most frequently investigated issue [3, 4]. The measured quantity is the thermopower \( S = \sum_{\sigma} S_{\sigma} \) with \( S_{\sigma} = -\Delta V_{\sigma}/\Delta T \) the spin-resolved one denoting induced spin bias voltage \( \Delta V_{\sigma} \) by a temperature gradient \( \Delta T \). In spin caloritronics, the counterpart of Seebeck effect is the spin Seebeck effect (SSE) [5]. It refers to the generation of pure spin current in the absence of charge electrical current, or spin bias denoting spin-resolved chemical potentials. Since the interaction strength between electron spins is much weaker as compared to the electrostatic force, and then the SSE suggests a possibility of high-efficiency and low-energy nano-scale thermoelectric devices. It is
also promising in the detection of small temperature difference in low-dimensional systems [5], and has been extensively investigated in the fields of spin current rectifier [6], magnetic heat valves [7], quantum cooling [8], thermal spin-transfer torque [9], thermovoltaic transistor [10], thermal logic gates and thermal memory for quantum information processing [11]. After the pioneering work of K. Uchida in 2008 [5], the SSE has been continuously observed in various materials [12–21], including magnetic metals, ferromagnetic insulators, ferromagnetic metals, ferromagnetic semiconductors, nonmagnetic materials with a magnetic field, paramagnetic materials, antiferromagnetic materials, and even topological insulators.

In the definition of spin-dependent thermopower $S_\sigma$, the generated spin bias voltage $\Delta V_\sigma$ denotes the split mechanical potentials as $\Delta V_\sigma = \hbar (\mu_\sigma - \mu_d)/2$, and the spin-up and spin-down electrons are individually at different states $\mu_\sigma$ due to the existence of thermal bias $AT$. The spin bias is the driving force for electron transport and induces spin-polarized currents. In fact, from the Fermi-Dirac function $f_\sigma = 1/\exp [(\epsilon - \mu_\sigma)/k_BT_u] + 1$, one can expect that the driving force for spin-dependent electronic transport to come from a spin-dependent electrons' temperatures $T_{\mu_\sigma}$, whose function is similar to the spin bias $\mu_\sigma$. This is called as spin heat accumulation (SHA) realizable by an electric current from a ferromagnet into a nonmagnetic material [7, 22–26]. Usually, the SHA emerges with the accompany of spin bias voltage and is quite weak as compared to the latter. In recent experiment [24], the magnitude of SHA can be enhanced to as high as about several kelvins.

Very recently, thermoelectric effect [27–31] was proposed to be used for detecting Majorana zero modes (MZMs), a kind of quasi-particles of Majorana fermions having zero energy that can be realized in nano-scale topological superconductors [32, 33]. They have their own antiparticle and charge neutral [32–35], and have potential applications in fault-tolerant quantum computation and energy-saving spintronic devices [36]. Due to their exotic zero-energy, chargeless properties, the detection of them is the central topic in studies relating to MZMs. Currently, the most important detection means is the electrical tunnel spectroscopy by applying a voltage $\Delta V$ across the nanowire with MZMs and to observe the associate current. The MZMs induce a zero-bias anomaly in the differential of electrical conductance [32, 33, 37], which is viewed as the evidence of MZMs. But this zero-bias anomaly in the conductance may also induced by some other mechanisms, for example, the Kondo effect [35]. Therefore, some other schemes, including the thermoelectric effect tuned by MZMs, were then continuously proposed in recent years. It was proved that the electron-hole symmetric nature of the MZMs which results in null thermoelectric effect can be effectively broken in a structure with a quantum dot (QD) coupled to topological superconductor hosting MZMs [27, 28]. Large value of thermopower satisfying Mott formula was proposed for detecting temperature of MZMs [19]. Such a system is possible to deduce information of the dissipative decay of MZMs [29]. In a two-terminal structure with a QD sandwiched between two leads and side-coupled to MZMs, a global sign reversion of the thermopower induced by MZMs was studied by López et. al. Such a phenomenon is caused by the direct MZM-MZM coupling [28]. The sign change and abnormal enhancement of thermopower by coupling between the QD and MZMs were also studied in some subsequent works [30, 31].

In our recent work, we have proposed a scheme composing of a QD side-coupled to MZMs to detect the SHA in terms of sign change of thermopower [38]. The mechanism is that the thermopowers of different spin components will change signs at different temperatures due to the QD-MZMs coupling. The SHA denoting spin-dependent temperature then can be inferred by the change of spin-polarized thermopower varying with respect to the magnitude of SHA. This task can also be fulfilled by observing the charge thermopower, which is much easier to be measured in experiments. In the previous work [38], we proved that the transition temperature of the thermopower depends on the QD-MZMs coupling strength, and the ferromagnetism of the two leads connected to the QD. Above or below the transition temperature, both 100% spin-polarized or pure spin thermopower will emerge due to the influences of SHA and MZMs. In the present paper, we study the properties of thermopower in a QD connected to the left and right leads with SHA, and also to a topological superconductor nanowire hosting MZMs. We focus our attention of the spin-resolved thermopower induced by the existence of MZMs, which are coupled to electrons on the QD with spin-dependent coupling strength. Our numerical results show that 100% spin-polarized and pure spin thermopower can be obtained by varying several system parameters, such as spin-polarization of the QD-MZM hybridization interaction, inter-MZM coupling strength, magnitude of the SHA, and the dot levels.

### 2 MODEL AND METHODS

The system Hamiltonian we study can be written in the following form [30, 31, 38].

$$H = \sum_{k_{hf}} \epsilon_k c_k^{\dagger} c_k + \sum_{\sigma} \epsilon_d d_{\sigma}^\dagger d_{\sigma} + Ud_{\uparrow}^\dagger d_{\uparrow} d_{\downarrow}^\dagger d_{\downarrow} + \sum_{k_{hf}} (V_{g\sigma} c_k^{\dagger} c_k + H.c) + H_{MZMs},$$

(1)

where $c_k^{\dagger}$ ($c_k$) is the creation (annihilation) operator for an electron with momentum $k$, energy $\epsilon_k$ in the non-interacting leads $= L, R$. $d_{\sigma}^\dagger (d_{\sigma})$ is the electron creation (annihilation) operator having gate voltage tunable energy level $\epsilon_{g\sigma}$ spin-$\sigma$ and intradot Coulomb interaction $U$. The coupling strength between the QD and the leads is described by $V_{g\sigma}$. The last term $H_{MZMs}$ in Eq. 1 is for the MZMs formed at the ends of a topological superconductor nanowire. Here we assume that the QD is side-coupled to one mode of the MZMs and [39],

$$H_{MZMs} = i \Delta_M \eta_1 \eta_2 + \sum_\sigma \lambda_{\sigma} (d_{\sigma} - d_{\sigma}^\dagger) \eta_1,$$

(2)

in which $\Delta_M$ is the inter-MZM coupling strength with $\eta_1 = \eta_1^\dagger (j = 1, 2)$ and $\{\eta_1, \eta_2\} = \delta_{i,j}$. The spin-dependent hybridization strength between the MZM and electrons on the QD is $\lambda_{\sigma}$. We transform the Majorana operator $\eta_1$ to the regular
fermionic operators \( f \) as [39] \( \eta_1 = (f^\dagger + f)/\sqrt{2} \) and \( \eta_2 = i(f^\dagger - f)/\sqrt{2} \), and then \( H_{\text{MZMs}} \) is rewritten as

\[
H_{\text{MZMs}} = \Delta_M \left( f^\dagger f - \frac{1}{2} \right) + \frac{1}{\sqrt{2}} \sum_{\sigma} \lambda_\sigma \left( d_\sigma - d_\sigma^\dagger \right) \left( f^\dagger + f \right).
\]  

In this paper, we study the thermopower in linear response regime (infinitesimal bias voltage \( \Delta V \) and temperature bias \( \Delta T \)) which is calculated from \( S_\sigma = -k_B T \left( \partial \mu / \partial T \right)_\sigma \), where the integrals are [28–31],

\[
K_{n,\sigma} = \frac{1}{\hbar} \int (\epsilon - \mu)^n \left[ \frac{\partial f_\sigma(\epsilon)}{\partial \epsilon} \right] \zeta_\sigma(\epsilon) \frac{d\epsilon}{2\pi},
\]

in which \( \hbar \) is the reduced Planck’s constant, and \( \mu \) is the leads’ chemical potential. The spin-dependent equilibrium Fermi distribution function is written as \( f_\sigma(\epsilon) = 1/[1 + \exp [(\epsilon - \mu)/k_B T_{eq}] \) with \( k_B \) the Boltzmann constant and \( T_{eq} \) the spin-dependent equilibrium temperature known as SHA in the leads. Here we set the spin-resolved temperatures in the leads to be \( T_1 = T + \delta T/2 \) and \( T_1 = T - \delta T/2 \) with \( T \) the system equilibrium temperature. The transmission coefficient \( \zeta_\sigma(\epsilon) \) in the above equation can be obtained by using the Dyson equation method combined with Keldysh nonequilibrium Green’s function technique as [28–31],

\[
\zeta_\sigma(\epsilon) = -2\Im G_{\sigma,\sigma}(\epsilon),
\]

where \( \Im \) is the imaginary part, \( G_{\sigma,\sigma}(\epsilon) \) is the Green’s function in the transmission coefficient, and \( \delta T \) is the temperature bias.

### 3 RESULTS AND DISCUSSION

In the following numerical calculations, we set the band width in the leads \( D = 40 \) as the energy unit, and \( \Gamma_L = \Gamma_R = 0.1 \). Other function in the transmission coefficient can be calculated by the Dyson equation method as [40, 41],

\[
G_{\sigma,\sigma}^{\text{F},(0)} = \frac{1}{\epsilon - \epsilon_d + \frac{n_{\sigma}}{2\pi} \Im G_{\sigma,\sigma}(\epsilon)/2\pi},
\]

where \( \Gamma = \Gamma_L + \Gamma_R \) and the electron (hole) free retarded Green’s function is calculated from the equation of motion method as [40, 41].
constants are $e = h = k_B = 1$, with the leads’ chemical potentials $\mu_L = \mu_R = \mu = 0$. Figure 1 shows the influences of QD-MZM coupling strength on the electrical conductance and thermopower without SHA ($\delta T = 0$). In numerical calculations, the spin-dependent hybridization $\lambda_\sigma$ is set to be $\lambda_\uparrow = \lambda (1 - P)$ and $\lambda_\downarrow = \lambda P$, with $P$ the spin-polarization of the QD-MZM hybridization [40]. For the particular arrangement of $\lambda_\sigma$, we only present $G_\uparrow$ in Figure 1A and $S_\uparrow$ in Figure 1B, the behaviors of the spin-down component can be easily deduced. For $P = 0$, $\lambda_\uparrow = 0$ whereas $\lambda_\downarrow = 0$, and $G_\uparrow$ in Figure 1A shows the typical double-peak configuration due to the Coulomb-blockade effect [30, 31]. The peaks’ height is half of its quantum value $e^2/h$. With increasing $P$, the magnitude of $\lambda_\uparrow$ decreases and the peak’ height of $G_\uparrow$ increases, accordingly. For $P = 1$, the spin-up electrons on the QD are totally decoupled from the MZM as $\lambda_\uparrow = 0$ and then the peak of $G_\uparrow = e^2/h$. If the QD is coupled to a regular fermion, the peak value of the electrical conductance is zero, which is not shown here [39]. Such a change of the conductance $G$ induced by the QD-MZM coupling originates from the half-fermionic properties of MZM and was first found by Liu et. al., and is a strong evidence of the existence of MZMs. [39].

Figure 1B shows the spin-up thermopower $S_\uparrow$ varying with respect to the dot level $\varepsilon_d$ for different value of spin-polarization of QD-MZM coupling strength. For $\lambda_\uparrow = 0$ ($P = 1$), the thermopower has three zero points individually at $\varepsilon_d = 0$, $\varepsilon_d = -U/2$, and $\varepsilon_d = -U$ as shown by the green dash-dot-dot line [30, 31]. At the two sides of each zero point, $S_\uparrow$ develops two sharp peaks with opposite signs. From the calculation formulae of the thermopower and $K_{n,\sigma}$, one can see that the integrand of $K_{1,\sigma}$ is antisymmetric with respect to the chemical potential for symmetrical transmission coefficient $\zeta_{d}(\varepsilon)$. This indicates that, for $\lambda_\uparrow = 0$ the magnitude of $S_\sigma$ will be obviously suppressed in left-right symmetrical system as the tunneling of electrons will be compensated by the holes at the three zero points [27–30], which leads to null thermoelectric effect, i.e., zero thermopower. With increasing $\lambda_\uparrow$ (decreasing $P$), the value of the thermopower at the zero points keep unchanged, whereas at other dot level except for the electron-hole symmetric point $\varepsilon_d = -U/2$, it first decreases, reaching zero and then changes its sign. Such a sign change of the thermopower induced by QD-MZM coupling was also predicted by Chi et. al. in a recent work [30, 31]. We emphasize that in their work, the spin-up and spin-down electrons couple to the MZM with equal strength, i.e., the coupling strength between the QD and the MZM is spin-independent, and then the thermopower changes sign in the whole dot level regime. In the present paper, however, we consider the case of the spin-dependent QD-MZM coupling and find that the thermopower will not change its sign around $S_\sigma = -U/2$. The sign of $S_\sigma$ can be reversed by varying the value of $P$ indicates that the electron or hole tunneling direction is tunable by the MZM. As is known that the thermoelectric effect arises from the thermal bias applied between the two leads. We assume the left lead is hotter as compared to the right one, and then there...
or predicted and proposed to be an detection means for the because that in experiments the value of compared to the direct coupling between the MZMs. This is feasible means to probe the existence of the MZMs as thermopower by QD-MZM coupling may provide a more existence of Majorana fermions. The sign change of the thermopower induced by MZM-MZM coupling

thermopower. It is worth noting that the sign change of the thermopower at different dot levels, inducing sign change of the electronic character worth to be pointing out: one is that the sign change of the thermopower can be explained as follows: in general, the thermopower is positive for spin-up electrons on the QD with MZM, and the conductance becomes normal as shown by the green dash-dot-dot line. The thermopower in Figure 2B shows a clear sign reversion at a particular system temperature and magnitude of QD-MZM coupling, it enable that one spin component thermopower is zero whereas the other component is finite. In this way, a 100% spin polarized thermopower can be obtained. It is also possible that the thermopowers of the two spin components are of the same amplitude but have opposite signs, i.e., a pure spin thermopower without the accompany of charge thermopower. In spintronics, 100% spin-polarized and pure spin thermopowers are the corresponding currents or bias voltages.

We study influences of the SHA denoted by $\delta T$ [7, 23, 24] on the thermopowers at different dot levels in Figure 3. Here we set $p = 0.5$ so as to $\lambda_1 = \lambda_1$ and $S_T = S_T$ for $\delta T = 0$. It is found that $S_T$ in Figure 3A and $S_T$ in (Figure 3B) respectively approach to positive and negative values with increasing $\delta T$ [38]. This is because the spin-up and spin-down electrons are in different temperatures for finite value of $\delta T$, and then have corresponding different transition temperature of the thermopower. The charge thermopower $S_c = S_T + S_L$ in Figure 3C may also change its sign at dot levels of $\epsilon_d = -0.3$ and $-0.2$, whereas it keeps positive at $\epsilon_d = -0.1$. Interestingly, the charge thermopower $S_c = 0$ at about $\delta T = 3T/4$ for both $\epsilon_d = -0.3$ and $-0.2$, which provides a feasible way of changing the charge thermopower. In Figure 3D we present the result of pure spin thermopower $S_S = S_{T\uparrow} - S_{T\downarrow}$. There are three characters worth to be pointing out: one is that $S_S$ shows the perfect linear relationship with $\delta T$, which is ideal in detecting the strength of SHA; and the other is that $S_S$ is positive in the whole

FIGURE 4 | Thermopower for spin-up electrons in (A) and spin-down ones in (B) as functions of the dot level for varying MZM-MZM coupling strength $\Delta_M$ for indicated parameters.
range of $\delta T$. This indicates that a pure spin thermopower in the absence of charge thermopower can be generated by properly adjusting some system parameters, such as the dot level, magnitude of SHA, QD-MZM coupling strength or its spin polarization. At last, the magnitude of $S_{\uparrow}$ is comparable to that of the charge one, which is important in thermospin devices.

Finally in Figure 4 we present the influences of MZM-MZM coupling strength $\Delta_M$ on the spin-dependent thermopower. The most important property of the spin-up thermopower in Figure 4A is the sign change induced by $\Delta_M$, which has also been found in some previous work [28, 30, 31, 38]. The sign change of the thermopower by $\Delta_M$ can also be explained in terms of the shape of the electronic transmission function $\Gamma_{\sigma}(E)$, [1, 2] which not shown here. For the particular value of $P$, the spin-down thermopower in Figure 4B keeps unchanged. From the two figures one can see that $S_{\uparrow}$ and $S_{\downarrow}$ of the same amplitude may be opposite in sign, which enable the emerge of 100% spin polarized or pure spin thermopowers.

4 SUMMARY

In conclusion, we study properties of spin-dependent thermopower adjusted by MZMs in a QD connected to two normal metal leads. Our numerical results show that the spin-polarized thermopower will change its sign by varying the system equilibrium temperature with the help of interaction between the dot and one mode of the MZMs, which is useful in generating 100% spin-polarized or pure spin thermopowers. The SHA will change the signs of spin-up and spin-down thermopowers with enhanced magnitude. By the combined effect of the SHA and hybridization between the dot and MZM, the spin-polarized thermopower can be fully adjusted and enhanced, which is vital in energy-saving nanoscale devices.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

L-LS derived the formulas, performed partial numerical calculations, and wrote the original manuscript. Z-GF discussed the physical model, performed partial numerical calculations, and contributed in the paper writing.

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