A driven ferromagnetic chain with binary hopping as an efficient spin polarizer

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Abstract. Spectral properties of a magnetic chain and spin dependent electron transport through it are critically examined in presence of light irradiation. Two different kinds of bonds, long and short are taken into account where each site of the chain is composed of a finite magnetic moment which yields spin dependent scattering to generate polarized currents from a unpolarized one. The degree of spin polarization and its phase can selectively be adjusted with the help of irradiation parameters. All the results are valid for a wide range of physical parameters which suggest that the present proposal can be verified through a suitable laboratory experiment.

1. Introduction

Proper manipulation of electron spin has always been the fundamental goal of research in the field of ‘spintronics’, as with the knowledge of it spin based electronic devices can be designed efficiently, circumventing the use of traditional charge based electronic ones [1-6]. To have finite spin separation, a spin dependent scattering is required and that can be achieved in different functional materials. For instance, spin-orbit (SO) coupled systems where spin of electron is directly coupled to its orbital motion [7-15]. Other commonly known materials are the ferromagnetic ones, where spin-spin exchange interaction is involved for spin dependent scattering. For such a system, each lattice site contains a finite magnetic moment, associated with a net spin on it [16-19].

No doubt a large amount of work has already been done by researchers considering different ferromagnetic materials [16-19] over last few decades, exhibiting different new features. But to the best of our concern, no one has addressed the phenomenon of spin dependent transport through a magnetic material in presence of light irradiation. The enormous possibilities of getting non-trivial features in transport phenomena has recently been revealed by irradiating a sample, as it directly affects the energy band spectrum. Motivated with this fact, in the present work, we consider a simple ferromagnetic chain which is irradiated with light, and explore its spectral properties and the spin dependent transport through this chain under different input conditions. The chain is composed of two different bonds, referred as long and short (see Fig.1), and it is connected to two non-magnetic contact leads to form a nanojunction for electron transfer.
Following a Tight-Binding (TB) framework we include the effect of irradiation using the well known Floquet-Bloch ansatz [20-22] and compute spin polarization through Green’s function approach [23,24]. What we find that the spectral properties and spin polarization are strongly affected by the light. Our analysis provides a new prescription of getting spin selective electron transmission through a spin polarized device which can be a new boost in the area of spintronic research.

The present work is arranged as follows. With the above brief introduction (Sec.1), in Sec. 2, we describe the model i.e., the magnetic chain and the theoretical formulation. All the numerical results are discussed in Sec. 3 and finally we conclude in Sec.4.

2. Magnetic quantum system and theoretical framework

2.1. Magnetic chain and Tight-Binding Hamiltonian

The functional element that is used to produce spin polarized current is shown schematically in Fig.1. The chain is made up with two bonds, long (L) and short (S), and each site (n) of the chain comprises a finite magnetic moment ($\vec{h}_n$) associated with a net spin in it. $\vec{h}_n$ is the spin flip parameter which is responsible for spin dependent scattering [19]. Here it is relevant to note that the strength of $\vec{h}_n$ is usually too large [25] compared to the SO coupling strength which thus provides much larger separation between the up and down spin bands. The magnetic chain is finally irradiated with light (shown by the curly arrows in Fig.1) which is the central factor of our analysis.

In order to describe the quantum system we use a TB framework. Under nearest-neighbour hopping (NNH) approximation, TB Hamiltonian of the magnetic chain in absence of irradiation reads as [19]

$$H_M = \sum_n c_n^\dagger (\epsilon_n - \vec{h}_n \cdot \vec{\sigma}) c_n + \sum_n (c_{n+1}^\dagger t_{\sigma} c_n + c_n^\dagger t_{\sigma} c_{n+1})$$

$\epsilon_n$ is the site energy and $\vec{h}_n \cdot \vec{\sigma}$ denotes the spin dependent scattering term where $\vec{\sigma}$ is the Pauli spin vector. $t_{\sigma}$ corresponds to the NNH integral and depending on the L and S bands it becomes $t_L$ and $t_S$ respectively where $t_L < t_S$. When the sample is irradiated, the NNH gets modified.
light effect using the minimal coupling scheme following the Floquet-Bolch ansatz [20-22]. The modified hopping reads as

\[ t_\alpha \rightarrow t_\alpha \frac{1}{\mathcal{Z}} \int_0^\infty e^{i\omega t} e^{i\mathbf{A}_\alpha} d\tau \]  

(2)

where \( \mathbf{A}_\alpha \) is the unit vector associated with the nearest-neighbor sites, \( \mathcal{Z} \) is the time period and \( \mathbf{A} \) is the vector potential. Here we assume the homogeneous field and write \( \mathbf{A} \) as [20-22]

\[ \mathbf{A}(\tau) = \left\{ A_x \sin(\omega \tau), A_y \sin(\omega \tau + \phi) \right\} \]

(3)

where \( \phi \) is the phase factor, \( \omega \) is the frequency and \( A_x, A_y \) are the amplitudes.

To study transport phenomena through the magnetic chain, we need to connect it with two contact leads. We assume that the leads are semi-infinite, non-magnetic and reflectionless. A similar kind of TB Hamiltonian as given above, apart from magnetic interaction and irradiation effect, is used to describe them. We refer the site energy and NNH integral in the leads as \( \varepsilon_0 \) and \( t_0 \) respectively.

2.2. Theoretical framework

To determine spin polarization co-efficient, the first and the foremost thing that we need to calculate is the spin dependent transmission probabilities for the lead-magnetic chain-lead nanojunction. Referring the contact leads as lead-1 and lead-2 we compute transmission probabilities, following the Green’s function approach, using the formula [23]

\[ T_{\sigma,\sigma'} = \text{Tr} \left[ \Gamma_1 G' \Gamma_2 G'' \right] \]

(3)

where \( \Gamma_1 \) and \( \Gamma_2 \) are the coupling matrices and \( G' \) (\( G'' \)) is the retarded (advanced) Green’s function. \( G' = G'^{\dagger} \) carries the essential information of the contact leads and it can be expressed as [23]

\[ G' = \left( E - H_M - \Sigma_1 - \Sigma_2 \right)^{-1} \]

(4)

Where \( \Sigma_1 \) and \( \Sigma_1 \) are the self energy matrices introduced to incorporate the effects of the side attached leads. From Eq. (3), we get the pure (\( \sigma = \sigma' \)) and spin flip (\( \sigma \neq \sigma' \)) transmission probabilities. With these factors we define the net up and down spin transmission probabilities across the junction as

\[ T_\uparrow = T_{\uparrow\uparrow} + T_{\downarrow\uparrow} \]
\[ T_\downarrow = T_{\uparrow\downarrow} + T_{\downarrow\downarrow} \]

(5)

Finally, we compute the spin polarization coefficient (\( P \)) from the relation [23]

\[ P = \frac{T_\uparrow - T_\downarrow}{T_\uparrow + T_\downarrow} \]

(6)

Here, \( P = \pm 1 \) gives 100% up or down spin polarization, while \( P = 0 \), indicates vanishing polarization.
3. Results and discussions

The results are categorized into two parts. In the first part, we concentrate on the spectral properties of the magnetic chain which are essential to understand the explicit dependences of different physical quantities on spin selective transmission. The other part focuses on spin dependent transmission probabilities and spin polarization under different input conditions.

Before discussing the results, we mention the parameter values those are kept constant throughout the numerical computations. We choose the lengths of the short and long bonds as $1\,A^r$ and $1.25\,A^r$ respectively, and set the hopping strengths in these bonds as $t_s = 1\,eV$ and $t_l = 0.5\,eV$. All the magnetic moments are assumed to be aligned along $+Z$ direction, and thus $\theta_n = 0$, also set $\phi_n = 0\ \forall\ n$. For the contact leads, the site energy $\varepsilon_0 = 0$ and NNH integral $t_0 = 2\,eV$. The chain-to-lead coupling strength is fixed at $1eV$. All the results are computed at the high frequency limit $\hbar\omega \gg t_{s(f)}$. As the system is one-dimensional, the effects of $A_x$ and $\phi$ will no longer be observed. Here, $N$ is always taken as odd to have equal number of long and short bonds.

3.1 Spectral Properties

We start analyzing the spectral properties of the magnetic chain in absence of irradiation. Figure 2 shows the eigenenergy spectra of the magnetic chain under different strengths of the spin flip parameters $h$ (we set $h_n = h \forall\ n$). Several interesting features are noticed. At a first glance, we see that for $h = 1$, three large bands appear which are separated by finite gaps. Among these three large bands, the outermost two are associated with the up and down spin channels, while the middle one is
the mixture of the two. If we would set \( h = 0 \), then instead of three, two bands would appear. The non-zero spin flip parameter misaligns the up and down spin channels and this misalignment can be controlled quite easily by adjusting \( h \). Now for each spin sub-space we get two large bands followed by a sharp energy line which passes through the centre of the gap. For instance, in Fig.2 (a), we get an energy level at \( E = -1 \) (associated with the up spin), and \( E = +1 \) (associated with the down spin), and the corresponding eigenstates are sharply localized at one edge of the chain. The appearance of such an energy level along with two large energy bands is the generic features of the dimer chain. For each of the up and down spin sub-Hamiltonians we get two large bands, and because of finite overlap across \( E = 0 \), we get total three energy bands (Fig.2 (a)).

![Graphs](image)

Figure 4: Spin dependent transmission probabilities and spin polarization for a 25-site dimer chain at different values of \( A_x \).
With increasing $h$, more shifting takes place between the channels and a situation arises depending on $h$, when the right and left most energy bands of the two spin channels just touch each other, providing a zero gap across $E = 0$ (Fig. 2(b)). If we increase $h$ further, then a complete separation takes place which yields 4 distinct large energy bands (Fig. 2(c)).

Comparing the spectra, we see that the energy eigenvalues for the localized states are $\pm h$. For the dimer chain, such modes which we can refer to as localized modes, appear at the effective site energies. As we set $\epsilon_{nn} = \epsilon_{n\bar{n}} = 0 \forall n$, the effective site energies for the up and down spin Hamiltonians are $-h$ and $+h$ respectively, and therefore we get these values.

Now, we focus on the energy spectra of the irradiated magnetic chain those are shown in Fig. 3, where energy eigenvalues are computed by varying $A_x$ at three distinct values of the spin flip parameter. Two noteworthy features are obtained and those are as follows. Firstly, the positions of the bands in energy scale can be shifted selectively by adjusting the irradiation parameter $A_x$. It is always desirable to have at least zero energy gap between the two spin bands for high degree of spin polarization. What we see here is that, even for the moderate values of $h$, for which a finite overlap exists between the up and down spin bands, a nonzero gap between them can be established by adjusting $A_x$ (Figs. 3(a) and (b)). Thus, much higher gap can be produced by irradiation when the energy spectrum is itself gapped for the irradiation free case (Fig. 3(c)). The above feature can be utilized to achieve large degree of spin polarization even for the magnetic materials having too low strength of $h$. Secondly, the overall widths of the allowed energy bands get reduced with increasing the strength $A_x$ exhibiting an oscillatory pattern. These characteristics are solely due to the modification of hopping integral in presence of irradiation.

3.2 Spin dependent transmission probabilities and spin polarization

With the knowledge of up and down spin channels we can now easily understand and estimate the allowed windows for finite spin transmission and the nature of spin polarization coefficients. For the energy zone(s) where only up/down spin channels are available, we get sp/down spin transmission, and accordingly up/down spin polarization ($P = +1/-1$). On the other hand, for the mixed regions i.e., where up and down spin channels are available, both the spins can propagate and depending on the dominating channel we get a net polarization. In this case the degree of polarization naturally gets reduced ($|P| < 1$). For the complete overlap $P$ becomes zero. These features are clearly reflected in the spectra given in Fig. 4. The key aspect that we want to establish here is that the degree of spin polarization can be modulated significantly with the help of light irradiation, following the modifications of up and down spin channels. For higher $A_x$, almost 100% polarization is obtained for the entire allowed energy zones which is undoubtedly interesting and important as well.

4. Conclusion

In the present work, for the first time, we investigate theoretically the spectral properties of a dimer magnetic chain and spin dependent electron transfer through it in presence of light irradiation. Employing a tight-binding framework we include the irradiation effect following the Floquet-Bloch ansatz. The spin dependent transmission probabilities are calculated using the Green’s function formalism. Several interesting and important results are obtained those are summarized as follows.

- Two wide energy bands followed by a large gap appear for each spin sub-Hamiltonian. Along with this a sharply localized edge mode is obtained.
The positions as well as the widths of different energy bands are significantly influenced by the irradiation.

Gap opening or gap closing between the bands can be made by tuning the irradiation parameter.

Almost cent percent up/down spin polarization can be achieved by controlling the irradiation.

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