Engineering magnetoresistance: a new perspective

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Abstract

A new proposal is given to achieve high degree of magnetoresistance (MR) in a magnetic quantum device where two magnetic layers are separated by a non-magnetic (NM) quasiperiodic layer that acts as a spacer. The NM spacer is chosen in the form of well-known Aubry–André or Harper (AAH) model which essentially gives the non-trivial features in MR due to its gaped spectrum and yields the opportunities of controlling MR selectively by tuning the AAH phase externally. We also explore the role of dephasing on magnetotransport to make the model more realistic. Finally, we illustrate the experimental possibilities of our proposed quantum system.

Keywords: giant magnetoresistance, dephasing effect, externally controlled GMR, AAH spacer

(Some figures may appear in colour only in the online journal)
Figure 1. Schematic diagram of the nano-junction to explore magneto-resistive effect, where a fixed magnetic layer and a free magnetic layer is separated by a non-magnetic spacer (light yellow region). The left and right ends of the magnetic and non-magnetic layers are connected with semi-infinite non-magnetic perfect electrodes.

think of a device which on one hand will be very small in size, geometrically simple and easy to fabricate, and on the other hand, may exhibit a large magnetoresistance (in some cases it may reach up to 100%) at multiple bias windows. The 100% change in magnetoresistance (MR) will be obtained when finite propagation of charge carriers takes place for one configuration of the magnetic layers, while the charge flow gets perfectly blocked for the other configuration. In addition, we want to tune MR externally, without applying any magnetic field. If this kind of device is implemented, which has not been explored so far, then definitely it will boost the magnetoresistive applications in different aspects. The present work essentially focuses on that direction.

We substantiate our proposal with the junction set-up given in figure 1, where the NM layer plays the central role. One key idea is that we need to select the spacer in such a way that the bridging magnetic–non magnetic–magnetic (M–NM–M) system exhibits multiple energy bands and they are arranged, in energy scale, differently with the parallel (P) and anti-parallel (AP) configurations of the magnetic layers. Under this situation 100% MR can be obtained by selectively choosing the Fermi energy of the system, and this is one of our primary requisites. The other pivotal requirement is that the MR can be tuned externally. Both these two conditions will be fulfilled with the help of an AAH spacer [18–24], a quasicrystal, which has been a classic example of gaped systems. Quasicrystals are found to exhibit several non-trivial topological phenomena that are being considered as newly developed paradigms in the discipline of condensed matter physics. The diverse characteristic features of AAH models make them truly unique over the other quasicrystals, and several spectacular phenomena have already been revealed considering both the diagonal and/or off-diagonal versions through a reasonably large amount of recent theoretical and experimental works [18–24]. The AAH phases associated with the diagonal and off-diagonal parts, those are tuned externally and independently, regulate the energy band structure significantly, and thus, tunable physical properties are naturally expected.

To make the proposed model more realistic we include the effects of dephasing [24–28]. It is an important factor that can destroy the phase memory of charge carriers, and thus, it can affect the transport properties. Among many sources the most probable one is the electron–phonon (e–ph) interaction. Now inclusion of this effect has always been a challenging task, and although some prescriptions are available, most of them are based on density functional theory (DFT) within a non-equilibrium Green’s function (NEGF) formalism which are too heavy to implement properly and also very time taking [29]. But Büttiker came up with a simple and elegant idea to analyze the effect of dephasing [30–32], where virtual electrodes (voltage) are connected at each lattice sites of the bridging system (for illustration, see figure 2) those do not carry any net current, but they are responsible to randomize the phases of the electrons. \( N_{\text{space}} \) represents the total number of lattice sites in the NM spacer.

We define GMR as \( (G_P - G_{\text{AP}})/(G_P + G_{\text{AP}}) \), where \( G_P \) and \( G_{\text{AP}} \) correspond to net conductances for the parallel and anti-parallel spin configurations, respectively. Usually GMR is referred as \( (G_P - G_{\text{AP}})/G_P \). In this definition a situation may arise especially for the ballistic case, which can be understood from our forthcoming analysis, that \( G_{\text{AP}} \) drops almost to zero or in some cases it may vanish completely. Under this situation an infinite GMR will be obtained that we may call as absolute GMR, which cannot be shown in the graph. To avoid this, in our work, we mention GMR as \( (G_P - G_{\text{AP}})/(G_P + G_{\text{AP}}) \), and with this definition no physics will be altered. If we get 100% change in GMR, it means absolute GMR according to the other expression. In presence of environmental dephasing and other factors, though we get reasonable GMR, absolute GMR cannot be obtained which can also be understood from our upcoming discussion.

In order to calculate GMR, we need to determine conductance and we evaluate it from the spin dependent transmission probabilities, \( T_{\sigma\sigma'} \), following the Landauer conductance formula [33] \( G_{\sigma\sigma'} = (e^2/h)T_{\sigma\sigma'} \), where \( \sigma(\sigma') = \uparrow, \downarrow \). All these components, \( T_{\sigma\sigma'} \), are computed using the non-equilibrium Green’s function (NEGF) formalism, which is the
most suitable and standard technique to study transport properties. In this formulation, an effective Green’s function is formed by incorporating the effects of contact electrodes through self-energy corrections and it can be written as [33]:

\[ \Gamma_G = \left( E - H_c - H_S - H_D - \Sigma_S - \Sigma_D \right)^{-1}, \]

where \( \Sigma_S \) and \( \Sigma_D \) are the contact self-energies, and \( H_S \) and \( H_D \) are the tunnel Hamiltonians due to source (S) and drain (D). \( H_c \) is the Hamiltonian of the bridging conductor which is a sum \( H_c = H_M + H_{NM} \), where \( H_M \) and \( H_{NM} \) are the Hamiltonians associated with the magnetic and non-magnetic parts, respectively. We describe all these Hamiltonians within a tight-binding (TB) framework. Using the above Green’s function we evaluate spin dependent transmission probabilities through the Fisher-Lee relation [34]

\[ T_{SD} = \text{Tr} \left[ \Gamma_S^\sigma G^\sigma \Gamma_D^\sigma G^\sigma \right], \]

where \( \Gamma_q^\sigma \)’s \( (q = S, D) \) are the coupling matrices.

The spin dependent scattering mechanism exists only in the magnetic layers, separated by a NM spacer, and considering this effect the TB Hamiltonian of the magnetic layer reads as [35–37]

\[ H_M = \sum_n \epsilon_n (\epsilon_n - h_n) c_n + \sum_n \left( \epsilon_n t c_n + h.c. \right), \]

where \( c_n, \epsilon_n, t \) are the Fermionic operators, and \( \epsilon_n \) and \( t \) are the \( (2 \times 2) \) diagonal matrices associated with site energy \( \epsilon_n \) and nearest-neighbor hopping (NNH) integral \( t \) of up and down spin electrons. \( h_n, \sigma \) is the spin dependent scattering term where \( h_n \) is the strength of magnetic moment at site \( n \) and \( \sigma = (\sigma_x, \sigma_y, \sigma_z) \) is the Pauli spin vector with \( \sigma_z \) in diagonal

Figure 3. Illustration of GMR in presence of a perfect spacer \((W = 0)\). In (a) and (b), the dependence of net conductance \( G \) (red line) as a function of Fermi energy is shown for the parallel and anti-parallel configurations, respectively, and in each of these two spectra density of states (DOS) (sky blue color) is superimposed. In (c), a density plot is given to describe the simultaneous variation of GMR with dephasing strength \( \eta \) and Fermi energy \( E_F \). The effect of \( \theta \) (we set \( \theta_i = \theta \forall i \)) of the free magnetic layer (as the magnetic moments in the other layer are always fixed and aligned along +Z direction) on GMR is presented in (d) for some typical dephasing strengths \( \eta \). The maximum change is obtained for \( \theta = \pi \), as expected. Finally, in (e) and (f) the allowed energy windows for the three different layers are drawn, to have a complete idea of transmitting zones for the two spin configurations. Unless otherwise stated we take only two different values of \( \theta \) for the free layer to get the parallel and anti-parallel configurations. The other common parameter values are: \( \epsilon_0 = 0, t_0 = 2, \epsilon_{n\uparrow} = \epsilon_{n\downarrow} = 0, h = 1, N_{\text{fixed}} = N_{\text{free}} = 10 \) and \( N_{\text{spacer}} = 20 \).
representation. The orientation of any magnetic moment is described by the usual polar angle $\theta_i$ and azimuthal angle $\varphi_i$ in spherical polar co-ordinate system. For the NM spacer a similar kind of TB Hamiltonian, apart from the term $h_{n, \sigma}$, is used. Now, in presence of AAH modulation, the site energy of the spacer becomes \[ \epsilon_{n+1} = \epsilon_{n} + W \cos(2\pi b n + \phi), \] where $W$ is the strength of modulation and $b$ is a constant factor that can be a commensurate or an incommensurate one. For the incommensurate AAH model we choose $b$ as the golden mean i.e. $(1 + \sqrt{5})/2$. The other physical parameter $\phi$ in the site energy expression, the so-called AAH phase, plays an important role and it can be tuned externally with suitable set-up \[19, 22\]. We will critically examine its effect on GMR.

The TB Hamiltonians for the source and drain read as

\[ H_S = H_D = \sum_n a_n^\dagger t_0 a_n + \sum_n \left( a_{n+1}^\dagger t_0 a_n + \text{h.c.} \right), \]

where different terms correspond to the usual meanings. These electrodes are coupled to the bridging system via the coupling parameters $\tau_S$ and $\tau_D$, respectively. We assume S and D as perfect, semi-infinite, one-dimensional and non-magnetic.

In order to include dephasing effect following the Büttiker prescription we need to couple virtual electrodes, similar to real electrodes, at each lattice site of the conductor (see figure 2). All these electrodes are parametrized identically with S and D, and they are non-magnetic. The coupling strength (also referred as the dephasing strength) between the spacer and the dephasing electrodes is described by the parameter $\eta$. Now, to have the condition that these electrodes are not carrying any finite current, we have to adjust potentials ($V_m$) of the virtual electrodes accordingly, such that the voltage drop across each of these electrodes is perfectly zero. That is in principle possible with the application of a finite bias across the contact electrodes S and D i.e. $V_S = V_D$ (say) and $V_0 = 0$. Under this situation, the effective spin dependent transmission probability is expressed as \[32\]: \[ T_{m\sigma}^{\text{sp}} = T_{\sigma\sigma}^{\text{sp}} + \sum_m T_{m\sigma}^{\text{spD}} V_m / V_0. \]

Before analyzing the results let us mention the values of the physical parameters those are common throughout the calculations. The on-site energies for the perfect lattice sites are chosen as zero, and they are same for both up and down spin electrons. The NNH integral, $t_0$, in S and D is fixed at 2, and the other NNH integrals along with contact-to-conductor coupling strength i.e. $t_\sigma$, $\tau_S$ and $\tau_D$, are set at 1. As the dephasing strength $\eta$ is not common for all figures, we specify it in the appropriate places during our analysis. The strength of magnetic moments $h_{n} = h \forall n$ and the azimuthal angle $\varphi$ ($\varphi = \varphi \forall n$) are fixed at one and zero, respectively. The number of sites in the fixed and free magnetic layers are referred as $N_{\text{fixed}}$ and $N_{\text{free}}$, and we set them at 10. On the other hand, for the NM spacer we specify the total number of atomic sites by $N_{\text{spacer}}$, and unless specified otherwise, we set it at 20. All the energies are measured in unit of electron volt (eV).

Now we explain our results. As already stated, our central focus is to achieve a high degree of GMR and its suitable tuning. Before describing the tuning mechanism, let us start to analyze how to get high GMR. The key concept of getting high GMR is that we need to achieve higher conductance for one configuration of the free layer, and most importantly much lower conductance in the other configuration. If this lower conductance drops exactly to zero, then 100% change in MR will be obtained. This can be achieved considering the layered structure as illustrated in figure 3. For the parallel configuration, finite conductance is obtained within the range $-2 \leq E_F \leq 2$ (red line of figure 3(a)), whereas spin transmission gets perfectly blocked for both up and down spin electrons within the ranges $-2 \leq E_F \leq -1$ and $1 \leq E_F \leq 2$ in the anti-parallel configuration (red line of figure 3(b)). Thus, setting the Fermi energy anywhere within these two zones, viz. $-2 \leq E_F \leq -1$ and $1 \leq E_F \leq 2$, 100% GMR will be noticed. The allowed and the forbidden zones of different spin electrons for the two different configurations of magnetic moments can be understood from the energy bar diagrams shown in figures 3(e) and (f). The electron can transmit through the junction only when a common energy channel is found. What we see is that, for the parallel configuration one can get finite transmission, due to up or down spin electron, in the range $-2 \leq E \leq 2$, among which $-1 \leq E \leq 1$ is the overlap region for both the two spin electrons. This scenario is exactly reflected in the spectrum figure 3(a). When the magnetic moments of the free layer get flipped to make an anti-parallel configuration, the situation becomes more interesting. From the energy bar diagram figure 3(f) we can see that only within the range $-1 \leq E \leq 1$ both the up and down spin electrons can propagate, while all other zones are blocked. This is the key advantage of a layered structure. More and more selective transmitting zones can be generated by combining more number of magnetic and NM spacers, which we check through our detailed calculations, and thus more controlled transmission will be obtained. Comparing the spectra given in figures 3(a) and (b) it is now clear that 100% change in resistance can be possible by selectively choosing the Fermi energy.
The effect of dephasing is quite interesting. From the simultaneous variation of GMR with \( \eta \) and \( E_F \) (figure 3(c)), we can see that for a reasonable dephasing strength a high degree of GMR is obtained. With increasing \( \eta \) it gradually decreases, and eventually drops to zero for large enough strength, as expected.

Now, to examine the role of \( \theta \) on GMR, in figure 3(d) we plot GMR as a function of Fermi energy \( E_F \) for both the two orientations of magnetic moments, where the results in (a) and (b) are given for the incommensurate (\( b = \text{golden mean} \)) AAH spacer, and in (c) and (d) the results are presented for the commensurate (\( b = 1/10 \)) one. To compute these results, we set the AAH modulation strength \( W = 1 \) and the phase \( \phi = 0 \). Comparing the conductance spectra, the appearance of high degree of GMR at selective Fermi energies can easily be understood. The role of phase \( \phi \) on GMR is illustrated in (e) considering an incommensurate AAH spacer with \( W = 1.5 \), and finally, in (f) the effect of the spacer size is established where we fix \( W = 1 \) and \( \phi = 0 \). The different colors in (e) and (f) correspond to the results for the identical dephasing strengths as taken in figure 3(d). For (a)–(e) we choose \( N_{\text{space}} = 20 \). The other common parameter values are: \( \epsilon_0 = 0, \ t_1 = 2, \ h = 1 \), \( N_{\text{fixed}} = N_{\text{free}} = 10 \) and \( \theta = 0 \).

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...be performed externally [19, 22]. In this context it is relevant to note that few other proposals have also been made in different set-ups for possible tuning of MR externally [38–40]. For instance, considering a graphene heterostructure Bala Kumar et al [38] have shown that a large MR can be achieved upon the application of magnetic field, employing the specific properties of wave functions in the field and zero-field cases. On the other hand, in another work by Bala Kumar and co-workers [39] it has been established that band engineering can be possible in graphene nanoribbon by applying external magnetic field which leads to a large change in MR. With these proposals we get a clear confidence for implementing a new prescription of externally controlled mechanism of MR. Our work, thus definitely a new addition along this line.

Finally, to test how the results are sensitive to the size of the AAH spacer, in figure 5(f) we plot GMR by varying the length of the spacer considering \( \phi = 0 \) and \( E_B = 0 \). It exhibits pronounced oscillations providing almost constant amplitude with \( N_{\text{spacer}} \), which gives us a hint of choosing the dimension of the spacer for better performance.

From the results studied here we see that both for the ordered and AAH spacers, though GMR gets reduced with dephasing strength \( \eta \), high degree of GMR can still be observed for a reasonably large \( \eta \). This is one way (means the inclusion of dephasing) to include the environmental effects/disturbances, as put forward by Büttiker and many other groups. At the same time another few factors are also there that may affect the GMR. For instance, bulk disorder and/or edge vacancies, depending on the specific geometry of the conducting junction. It is true that disorder modifies the transport properties [41–43], but as GMR is the ratio between two conductances, significant change in GMR will not be noticed even for moderate disorder strength, which can also be confirmed from our results considering the AAH spacer (AAH model is called as the correlated disordered one). For strong enough disorder, when the states are almost localized, naturally we cannot expect any such phenomena.

Now, considering the unique and diverse characteristic features of AAH lattices, one proposition may come to our mind that instead of using an AAH spacer between two magnetic layers we can think about a GMR set-up where the effect of AAH potential is directly implemented into the magnetic layers, removing the spacer region. Of course the opportunity of energy band engineering will be still there by changing the AAH phase, but in the absence of NM spacer, two magnetic layers will then interact with each other because of the magnetic exchange interaction among them, which essentially affects the magnetic layers. To avoid this magnetic interaction, the inclusion of a NM layer is highly recommended, as used in other GMR studies.

For experimental realization of our proposed model, we can think about a set-up given in figure 6 where two magnetic layers are separated by a 2D lattice subjected to a transverse magnetic field \( B \), the so-called quantum Hall system. It is well-known that a 2D Hall system maps exactly to an effective 1D chain where the site energy gets modulated with the factor \( B \). Thus, selectively tuning the magnetic field one can design a spacer in the form of AAH chain, and in principle, can examine the results studied here.

In conclusion, we have established a new proposal to achieve better performance in magnetoresistive effect exploiting the unique features of correlated disordered lattice, that has not been reported so far in literature to the best of our knowledge. The persistence of the results even in presence of large dephasing strength gives us a confidence that the proposal can be substantiated experimentally with suitable set-up. What comes out from the entire analysis is that the essential mechanism of magnetoresistance is hidden within the non-trivial characteristics of different spacers, and here we have shown one example along this direction considering an AAH system. We also get a strong confidence about our claim following one recent work done by Wang et al [44]. Considering a bottom-pinned perpendicular anisotropy-based magnetic tunnel junction (p-MTJ, stacked with Tungsten (W) layers and MgO/CoFeB interfaces, they have shown that a large magnetoresistance \( \sim 249\% \) can be achieved, circumventing Tantalum (Ta) as the spacer as was used previously in other p-MTJ films. Thus, undoubtedly the spacer has the most significant role in magnetoresistive study. Although several propositions have been put forward, still more investigations are required for better performance.

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Figure 6. Proposed set-up to realize the model experimentally.
