Tunneling magnetoresistance dependence on the temperature in a ferromagnetic Zener diode

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Abstract. In the present work we focus on the study of the temperature dependence of the tunnelling current in a ferromagnetic Zener diode. We predict the tunneling magnetoresistance dependence on the temperature. Large doping concentrations lead to magnetic semiconductors with Curie temperature $T_C$ near or over room temperature and this will facilitate the introduction of new devices that make use of the ferromagnetism effects. According to our calculations the tunneling magnetoresistance has the form $TMR \propto (T_n^C - T_m^C)$.

1. Introduction
The recent progress in developing new semiconductor materials that show ferromagnetic characteristics at room temperatures is leading to a growing interest to replace charge with spin in signal processing devices. Spintronics is motivated by the belief that spin signal processing may yield advantages in terms of processing speed, power consumption or device density.

Dilute magnetic semiconductors (DMS) are showing good characteristics at rising temperatures and new DMS are being developed to achieve spin control at room temperature [1]. In an optimally doped DMS the density of carriers is approximately half that of the density of magnetic ions which is usually between $x = 5\%$ and $x = 15\%$ [1]. The well established DMS occur with one type of carrier. One of the most investigated materials is the III–V material (GaMn)As in which the Mn ion provides a localized spin $S = 5/2$ and also contributes a hole [1]. The holes are degenerate and strongly polarized at low temperatures [2]. The ferromagnetic III–V doped materials are all p type but there is much effort to find a compatible n type ferromagnetic semiconductor [3]. Magnetic properties have been seen in a number of magnetically doped oxides, particularly ZnO, TiO$_2$ and SnO$_2$ [4] all of which occur as n type semiconductors.

A PN junction of two highly degenerated semiconductors makes a Zener tunneling diode which has many applications [5] and adding magnetic functionality would enable more devices such as magnetic switching of microwave devices. Zener tunnelling has been observed in a ferromagnetic-nonmagnetic (GaMn)As/GaAs heterostructure, and a high spin polarization is observed optically [6]. The voltage dependence of the tunnelling current in a spin-polarized Zener diode is well fitted by the theory of a non-magnetic diode [2]. We are developing analytical [7] and numerical models [8] to study the transport in ferromagnetic Zener diodes. Using these models we have predicted the dependence of the tunneling current on the mean magnetization of the system and we have evaluated the tunneling magnetoresistance ($TMR$) for different values of the applied bias and temperatures in a theoretical both-sided-ferromagnetic diode.
The article is structured as it follows: Section 2 summarizes the effects of the ferromagnetism. Section 3 shows the results for tunnelling current and TMR dependence with the temperature in a ferromagnetic GaAs diode. Conclusions are drawn in Section 4.

2. Tunneling transport

The current through a tunnelling diode has three components [5]: the tunnelling current, the excess current and the diffusion current. The tunnelling current rises to a maximum at low voltage, about the lowest of the distances between the Fermi level and the conduction band in the n-side \((\varepsilon_n/q_e)\) and the valence band in the p-side \((\varepsilon_p/q_e)\). Then it falls to zero when bias increases over \((\varepsilon_n + \varepsilon_p)/q_e\). This fall in the I-V curve is known as negative resistance region and is produced by the overlapping of the density of carrier functions in both P and N sides.

The tunnelling of carriers through the bandgap is an important part of the carrier transport in highly doped PN junctions. There are two tunnelling mechanisms: the direct transition from band to band and the trap assisted tunnelling. The basic principles of the band-to-band tunnelling were explained by Kane [9]. The tunnelling probability, obtained from the WKB approximation, is given by \(T_t \approx \exp \left[-2 \int_{r}^{r'} |\kappa(r)| dr \right]\), where \(\kappa(r)\) is the wave vector associated to the carrier near the barrier and \(u\) and \(l\) are the classical turning points in the potential barrier. The tunnelling density of current is described as follows [9]:

\[
J_t \propto \int_{E_C}^{E_V} [F_C(\epsilon) - F_V(\epsilon)] T_t D_n(\epsilon) D_p(\epsilon) d\epsilon,
\]

where \(T_t\) is assumed to be equal for both directions, \(F_C(\epsilon)\) and \(F_V(\epsilon)\) are the Fermi-Dirac distribution functions and \(D_n(\epsilon)\) and \(D_p(\epsilon)\) are the density of states. Equation (1) shows that the tunnelling current depends on the tunnelling probability \(T_t\) as well as a supply function of electrons and holes, described by the density of carriers in each band.

2.1. Mean field theory in \((\text{III},\text{Mn})\text{V}\) alloys

The effect of the exchange interaction between the charge carriers and the localized magnetic moments on the energy band structure and the transport properties can be estimated by using a perturbation theory [10]. The total Hamiltonian describing the free carrier and magnetic moments on the energy band structure and the transport properties can be estimated by using perturbation theory [10]. The total Hamiltonian describing the free carrier and magnetic subsystems in the DMS is given by \(H_{\text{tot}} = H^{(1)} + H_{\text{exch}} + H_m\) where \(H^{(1)}\) gives the carrier energies in the spin-polarized band, \(H_{\text{exch}}\) takes account of the interaction between the free carriers and the magnetic ions and \(H_m\) the interaction between magnetic ions and the Zeeman energy when an external magnetic field is applied.

A first order correction of the band energies due to the exchange potential can be obtained, assuming external magnetic field, this is, no paramagnetic behavior of the material. The first order correction can be written as [10]:

\[
\Delta E_{\text{KS}} = E_{\text{be}} + \frac{\hbar^2 k^2}{2m^*} - \frac{\Delta}{2} (\delta_{\sigma\uparrow} - \delta_{\sigma\downarrow}),
\]

where \(\Delta = xJ_{\text{exch}} \langle S^z \rangle\) is the fist-order band splitting. In the mean field approximation, the average spin polarization of the magnetic moments, \(\langle S^z \rangle\), is given by \(x \langle S^z \rangle = x S B_S(y)\) where \(x\) is the Mn ions concentration and \(B_S(y)\) is the Brioullin function for the spin quantum number \(S\) with \(y = g_L \mu_B B_{\text{eff}} / k_B T\) and \(B_{\text{eff}}\) is the effective molecular field.

Figure 1 shows the calculated band splitting at \(B = 0\) \(T\) for \((\text{GaMn})\text{As}\) where \(J_{\text{exch}}^{pd} = 1.4\text{eV}, m^*_h = 0.5m_0, T_C = 110\ K\) and \(S = 5/2\). We see how the ferromagnetism effects disappear for temperatures over \(T_C\) and the splitting rises and saturates to a maximum value for low temperatures. The resulting band diagram at \(T = 0\ K\) is shown in figure 2. There are two
Figure 1. Temperature dependence of the band edge in a ferromagnetic semiconductor (GaMn)As at $B = 0$ T showing the band splitting when $T_C = 110 \, K$.

Figure 2. Band diagram for a GaAs diode at equilibrium. The dotted lines are the bands when the spin polarization is zero ($p = 3 \cdot 10^{20} \, cm^{-3}$ and $n = 0.7 \cdot 10^{20} \, cm^{-3}$).

conduction/valence band edges, one for electrons/holes with spin up and for electrons/holes with spin down. The tunnelling occurs between the two majority and the two minority bands or, if the relative magnetization of the layer is reversed, between the majority and the minority bands. We call these currents parallel current $I_p(V)$ and antiparallel current $I_{ap}(V)$.

3. Results

The tunneling current has been calculated for a theoretical GaAs diode, ferromagnetic on both sides in a range of temperatures between $0 \, K$ and $T_C$. Typical characteristic I-V curves are shown in figure 3, where the current through a non spin-polarized diode (solid line) and for the parallel and antiparallel configuration can be seen. The tunneling magnetoresistance ($TMR = \frac{I_p - I_{ap}}{I_p + I_{ap}}$) was evaluated at applied bias $V_a = \frac{\min(\varepsilon_n, \varepsilon_p) + \varepsilon_n + \varepsilon_p}{2q_e}$, which is half way between the maximum and zero tunneling current biases for a non spin-polarized diode. This bias value has been chosen because for higher values the TMR is expected to be lower because the excess and thermal current become important and they are not spin dependent. For lower biases the TMR is lower as can be seen in figure 3, since the tunneling current is dominated by the overlapping of high energy states which are less dependent on the splitting.

We sample the value of the $TMR$ at different temperatures to analyze its dependence at low and near $T_C$ temperatures. Results from three of the evaluated configurations are shown in figure 4 as the most significant: a symmetric diode (dashed green line) where the carrier concentration in each side of the diode is the same so they have the same $T_C = 110 \, K$, a P$^+$N diode with $T_C = 110 \, K$ in the P-side and $T_C = 27 \, K$ in the N-side and a PN$^+$ diode where $T_C = 110 \, K$ in the P-side and $T_C = 139 \, K$ in the N-side. We have fixed the $T_C$ in the p-side because it is the highest Curie temperature achieved for GaAs at the moment.

Several remarks can be extracted from figure 4. The highest values of the $TMR$ are obtained for temperatures near $0 \, K$, which is a consequence of the dependence of the magnetization and therefore of the splitting on the temperature as shown in figure 1. The most favorable configuration to obtain high $TMR$ values is the P$^+$N diode, although it is constrained to low temperature values, because for $T > 27 \, K$ the N-side loses its ferromagnetic properties and the TMR is no longer observable because it requires that both sides are ferromagnetic. PN$^+$ configuration shows low values of $TMR$, even at $0 \, K$. This can be explained from the low polarization of the carriers in the N-side where the maximum possible splitting is less than $0.1 \, eV$ at temperatures near $0 \, K$ and the kinetic energy of the higher energy carriers is around $0.4 \, eV$;
Figure 3. Tunnelling current and $TMR$ when the splittings of the p-band and n-band are near to 0.1 eV. The parallel (dashed, blue) and the antiparallel (dot-dashed, red) configurations are given as well as the current for zero spin-splitting (continuous, green).

Figure 4. $TMR$ dependence on the temperature for different N-side doping levels. The doping in the P-side is fixed to $3 \times 10^{20}$ cm$^{-3}$ which correspond with $T_C = 110$ K. The Curie temperatures in the N-side are 27 K (continuous, blue), 110 K (dashed, green) and 139 K (dot-dashed, red)

therefore, only a small part of the carriers are polarized. The symmetric configuration seems to be the best configuration to see good values of $TMR$ in the widest range of temperatures.

Another interesting result from our calculations was that, in a symmetric configuration, the $TMR$ dependence on the temperature has the form $TMR \propto (T_C^2 - T^n)$. In particular, for a carrier concentration level that correspond with $T_C = 110$ K, $n = 3$.

4. Conclusions

We extend our previous developed analytical model to add the temperature dependence of the ferromagnetic properties of the DMSs. We found that the $TMR$ has a strong dependence on the temperature as well as on the relative doping values of both diode sides. We conclude that the best configuration to see high $TMR$ values at high temperatures will be a symmetric diode. However, the highest values of $TMR$ can be achieved from non-symmetric configurations that guarantee high polarization level of the carriers in, at least, one of the diode sides; but these values of the $TMR$ are constrained to low temperatures.

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