

Spin transport through GaAs/GaMnAs/GaAs

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This work addresses spin-dependent transport in the heterostructure p -GaAs/GaMnAs/ p -GaAs. The diluted ferromagnetic semiconductor GaMnAs layer behaves, within mean field approximation, as a potential well for spin-down carriers and a potential barrier for spin-up ones. Thus the transport would be spin-dependent. The goal of this work is to devise spin filters relevant for spin-dependent optoelectronics. A spin polarized transmission is obtained. An oscillatory behavior of transmission coefficient is shown and explained by quantum resonance. Our results indicate that the transmission and the polarization can be tuned by tuning the incident energy.

PACS numbers:

I. INTRODUCTION

III-V compound semiconductor heterostructures have been the test bench for new ideas and a rich field for new physics, owing to its capability of obtaining atomically abrupt heterojunction interfaces in a virtually impurity-free environment. It is also used in electronic and optical devices such as high-speed transistors and lasers. Magnetism, especially ferromagnetism, has not been a part of the activity in III-Vs because of the lack of material technologies that allow us to introduce magnetic cooperative phenomena into III-V-based heterostructures. The success in synthesis of magnetic III-Vs, alloys of III-Vs and transition elements like Mn [1], and subsequent discovery of ferromagnetism in them [2, 3], introduced a new and unexplored degree of freedom, which can be combined with all the freedoms we currently enjoy working with.

Electronic and optoelectronic semiconductor devices, controlled by a weak magnetic field, and electric-field controlled ferromagnetism in semiconductors[4] promise new functionality of memory, detectors, and light-emitting sources. Possible device implementations of spin electronics are high-electron-mobility transistors, Si/Si and GaAs/Si spin-valve transistors, spin light-emitting diodes, quantum computers, and integration of non-volatile storage and logic. Efficiency of spin injection depends on the interface quality; all-semiconductor structures should benefit the performance of spin-electronic devices. Recent achievement in materials research resulted in ferromagnetic semiconductor material lattice matched to III-V semiconductors: the ferromagnetic critical temperature in semiconductors $T_c = 110$ K has been observed in metallic samples of $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ ($x = 0.053$) epilayer[5, 6].

The discovery of ferromagnetism in diluted magnetic semiconductors (DMSs) can provide an opportunity to study spin-polarized transport phenomena, which make it possible to combine the information processing and data storage in one material. The origin of ferromagnetism in the DMS can be explained by using a picture in which uniform itinerant carrier spin mediates a long-range ferromagnetic order between the Mn^{2+} ions with spin $S = 5/2$. [7]

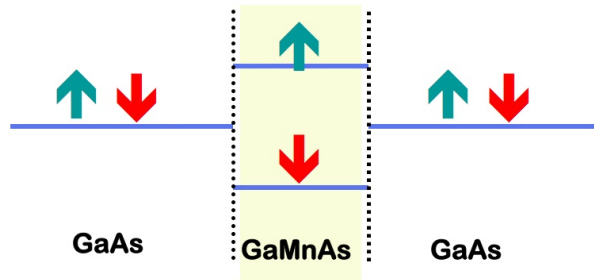


FIG. 1: The schematic diagram of carriers passing through the heterostructure p -GaAs/GaMnAs/ p -GaAs. The p-d exchange interaction would give rise to a spin-dependent potential. Spin-up carriers see a barrier while spin-down ones a well. Mn ions are aligned upward.

Electronic spin filters, i.e., devices which would produce spin-polarized injection currents, are relevant for spin-dependent optoelectronics [8]. Spin filters could be used to devise circularly polarized light sources, e.g., light emitting diodes and lasers, operating with polarized injection currents.

In this paper, we report the theoretical investigation on electronic spin filtering in perpendicular transport through a p -GaAs/GaMnAs/ p -GaAs heterostructure. In Sec. II we briefly explain the theoretical background. The calculations and results will be discussed in Sec. III. Conclusions are given in Sec. IV.

II. THEORETICAL BACKGROUND

We consider the heterostructure p -GaAs/GaMnAs/ p -GaAs as shown in Fig. 1, in which two GaAs layers are separated by a thin layer of ferromagnetic GaMnAs. They are assumed to be the $y-z$ plane and to be stacked along the x direction. For the GaMnAs layer, we apply a model with energy difference Δ between the highest energies of the majority and minority valence subbands, E_\uparrow and E_\downarrow , with the spins parallel and antiparallel to the local magnetization respectively. In the Fig. 2, E_0 is the average value of E_\uparrow and E_\downarrow , and E_F is the Fermi energy.

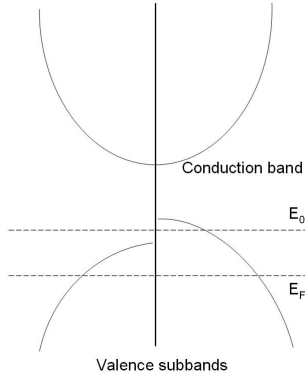


FIG. 2: Schematic illustration of valence subbands of a ferromagnetic GaMnAs.

The Hamiltonian in the GaAs layer can be given by:

$$H_{GaAs} = -\frac{\hbar^2}{2m^*} \nabla^2 \quad (1)$$

where is the kinetic energy with the effective mass m^* of a hole.

The hole Hamiltonian in the DMSs is given by:

$$H_{DMS} = -\frac{\hbar^2}{2m^*} \nabla^2 - \mathbf{h}(z) \cdot \sigma \quad (2)$$

where the first term on the right side is the kinetic energy with m^* the mass of a hole in GaMnAs and the second term is internal exchange with the molecule field $h(z)$ and σ the conventional Pauli spin operator. This term actually comes from the $p-d$ interaction with mean field approximation. It would give rise to a spin-dependent potential[9]. In this paper, we assume the spins of Mn ions are aligned upward. Via an antiferromagnetic interaction between holes and Mn ions, spin-up carriers see a barrier while spin-down ones a well, as seen in Fig. 1.

Assuming the GaMnAs layer is located between 0 and d , we then have three regions with different potential, $x > d$, $d > x > 0$, $x < 0$. By the continuity of wavefunction and its derivative, we can solve the wavefunction, and hence the transmission coefficient. For different spin species, the potential in the region $d > x > 0$ is different. Therefore we would have different wavefunctions Ψ_{\uparrow} , and Ψ_{\downarrow} , so are the transmission coefficients T_{\uparrow} , and T_{\downarrow} . Hence we obtain a spin-dependent transport. The spin-dependent transport is manifested by the current. The spin-dependent current density is given by

$$j_{\sigma}(r) = ev_x(k_x)T_{\sigma}(k_x) \quad (3)$$

where $v_x(k_x) = \hbar k_x/m$ is the x component of the carrier velocity, and k_x is the x component of the momentum.

To solve the tunneling problem, we calculate the effective potential coming from the magnetization of the DMS GaMnAs layer. It is also of practical interest to know the temperature dependence of transport. This

can be achieved by considering the temperature dependence of the average Mn spin $\langle S_z \rangle$ in the DMS GaMnAs layer. The temperature dependence of $\langle S_z \rangle$ would make the potential temperature dependent, thus making the transport temperature dependent.

III. CALCULATIONS AND RESULTS

A. Model

First we consider the carrier is in a potential as follows:

$$V(x) = \begin{cases} 0 & x < 0 \\ V_0 & 0 < x < d \\ 0 & x > d \end{cases} \quad (4)$$

The wavefunction is of the form:

$$\Psi = \begin{cases} e^{ikx} + re^{-ikx} & x < 0 \\ ae^{iqx} + be^{-iqx} & 0 < x < d \\ te^{ikx} & x > d \end{cases} \quad (5)$$

where $k = \frac{\sqrt{2mE}}{\hbar}$, and $q = \frac{\sqrt{2m(E-V_0)}}{\hbar}$. The coefficients r, a, b, t are to be determined. By the continuity of Ψ and Ψ' at $x = 0$ and $x = d$, we have

$$\begin{pmatrix} 1 & 1 \\ ik & -ik \end{pmatrix} \begin{pmatrix} 1 \\ r \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ iq & -iq \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

$$\begin{pmatrix} e^{iqd} & e^{-iqd} \\ iqe^{iqd} & -iqe^{-iqd} \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} e^{ikd} & e^{-ikd} \\ ik e^{ikd} & -ik e^{-ikd} \end{pmatrix} \begin{pmatrix} t \\ 0 \end{pmatrix}$$

Denote the above equations as:

$$M_1 \begin{pmatrix} 1 \\ r \end{pmatrix} = M_2 \begin{pmatrix} a \\ b \end{pmatrix} \quad (6)$$

$$M_3 \begin{pmatrix} a \\ b \end{pmatrix} = M_4 \begin{pmatrix} t \\ 0 \end{pmatrix} \quad (7)$$

Therefore we obtain:

$$\begin{pmatrix} 1 \\ r \end{pmatrix} = S \begin{pmatrix} t \\ 0 \end{pmatrix} \quad (8)$$

where $S = M_1^{-1}M_2M_3^{-1}M_4$ The transmission coefficient T then is determined:

$$T \equiv |t|^2 = \left| \frac{1}{S_{11}} \right|^2$$

$$= \left[1 + \frac{V_0^2}{4E(E-V_0)} \sin^2 \left(\frac{d}{\hbar} \sqrt{2m(E-V_0)} \right) \right]^{-1} \quad (9)$$

There are three situations in our scattering problem:

- $V_0 > 0$ and $E - V_0 > 0$, this is what we calculated above. To be noted, this is classically allowed.
- $V_0 < 0$ and $E - V_0 > 0$, we just need to do the transformation $V_0 \rightarrow -V_0$, then we obtain the corresponding transmission coefficient. This is also classically allowed.

- $V_0 > 0$ and $E - V_0 < 0$, this situation is classically forbidden. The momentum inside the potential barrier is imaginary:

$$q = i \frac{\sqrt{2m(V_0 - E)}}{\hbar} \quad (10)$$

Insert this into eq. (9), we obtain the transmission coefficient:

$$\begin{aligned} T &= \left\{ 1 + \frac{V_0^2}{4E(E - V_0)} \left[i \cdot \sinh \left(\frac{d}{\hbar} \sqrt{2m(V_0 - E)} \right) \right]^2 \right\}^{-1} \\ &= \left[1 + \frac{V_0^2}{4E(V_0 - E)} \sinh^2 \left(\frac{d}{\hbar} \sqrt{2m(E - V_0)} \right) \right]^{-1} \end{aligned} \quad (11)$$

Hereafter we use the obtained formula of transmission coefficient to investigate the spin transport of p -GaAs/GaMnAs/ p -GaAs heterostructure.

B. Effective potential in GaMnAs layer

To calculate the transmission coefficient of this heterostructure, the effective potential V_0 has to be determined. The effective potential is originated from the magnetization of the GaMnAs. In this work we calculate the magnetization of GaMnAs, and thus the corresponding effective magnetic potential under mean field approximation.

We first consider the magnetic Hamiltonian for one itinerant hole with spin s located r and one Mn ion with spin S located at R . Both of these magnetic subsystems can be described as [11]

$$H^h = J_{pd} \sum_I s \cdot S_I \delta(r - R_I) \quad (12)$$

$$H^{Mn} = J_{pd} \sum_i s_i \cdot S \delta(r_i - R) \quad (13)$$

Here, J_{pd} is the hole-Mn exchange coupling constant. In the mean-field approximation, these Hamiltonians become

$$H^h = g_h \mu_B s \cdot h^h \quad (14)$$

$$H^{Mn} = g_{Mn} \mu_B S \cdot h^{Mn} \quad (15)$$

where μ_B is the Bohr Magneton, g_h , and g_{Mn} are the Lande g -factor for holes and Mn ions, respectively. h^h and h^{Mn} are respectively the effective magnetic fields acting upon holes and Mn ions, and can be given as

$$h^h = \frac{J_{pd} N_{Mn} \langle S_z \rangle}{g_h \mu_B} \quad (16)$$

$$h^{Mn} = \frac{J_{pd} N_h \langle s_z \rangle}{g_{Mn} \mu_B} \quad (17)$$

Here $N_{Mn} = 4x/a_0^3$ is the density of Mn ions, with being the unit cell volume. The spin polarization of the Fermi

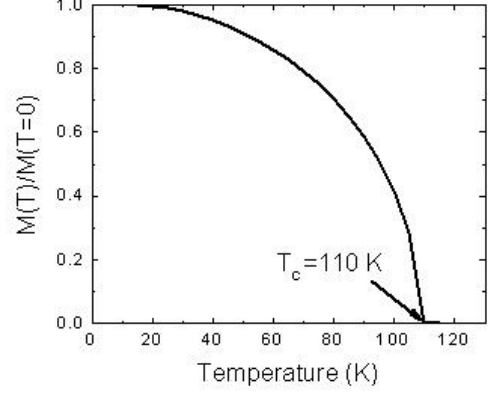


FIG. 3: The calculated magnetization of the GaMnAs

sea holes by the effective field h^h is given by

$$\frac{\langle s_z \rangle}{s} = \frac{1}{N_h} g_h \mu_B s D(\epsilon_F) h^h \quad (18)$$

where the density of states of the hole gas with effective mass m^* and the hole concentration p is $D(\epsilon_F) = (3\pi^2)^{-2/3} (3m^*/\hbar^2) p^{1/3}$. And the magnetic response of the impurity spin to the effective field h^{Mn} is given by

$$M^{Mn} = g_{Mn} \mu_B N_{Mn} \langle S_z \rangle = g_{Mn} \mu_B N_{Mn} S B_S \left(\frac{g_{Mn} \mu_B S h^{Mn}}{k_B T} \right) \quad (19)$$

where $B_S(x)$ is the Brillouin function. Therefore, within the spirit of a mean-field framework the magnetization of Mn subsystem is then given by

$$M^{Mn} = g_{Mn} \mu_B N_{Mn} S B_S \left(\frac{J_{pd} S N_h \langle s_z \rangle}{k_B T} \right) \quad (20)$$

which should be determined self-consistently with the hole magnetization

$$M^h = g_h \mu_B N_h \langle s_z \rangle = \frac{g_h \mu_B J_{pd} D(\epsilon_F)}{s^2 g_{Mn} \mu_B} M^{Mn} \quad (21)$$

Now the temperature dependence of spin-splitting energy can be obtained as $\Delta = 2|h|$, where the molecular field is $h = (J_{pd}/2g_{Mn}\mu_B)M^{Mn}$ from eq.(14), (16), and (19).

Temperature dependent magnetization and spin-splitting energy have been calculated self-consistently from eq.(20) and eq.(21) with the parameters $a_0 = 0.565 \text{ nm}$, $J_{pd} = 0.15 \text{ eV} - \text{nm}^3$ [12], $S = 5/2$, $s = 1/2$, $g_h = g_{Mn} = 2$, $p = 4.9 \times 10^{20} \text{ cm}^{-3}$ [13], $x = 0.05$ [14], and $m^* = 0.16m_0$ [15]. Fig.3 and Fig. 4 show the temperature dependent magnetization and spin-splitting energy which are calculated with (20) and (21). The Curie temperature is 110 K.

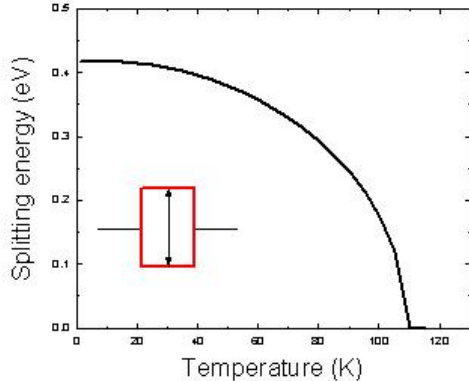


FIG. 4: The calculated spin-splitting energy due to the magnetization of GaMnAs.

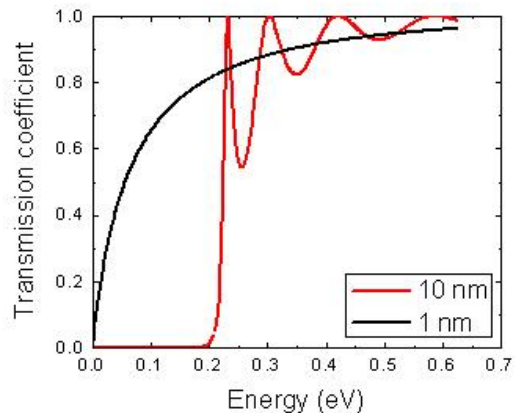


FIG. 5: Transmission coefficient as function of incident energy for spin-up carriers at zero temperature. The red curve is for GaMnAs thickness 10 nm; the black curve is 1 nm.

C. Transmission coefficient (T)

We calculate the transmission coefficient based on the above magnetization calculation. The potential barrier $V_0 = 0.21\text{eV}$ is obtained from the zero temperature magnetization of GaMnAs. Fig. 5 and Fig.6 shows plots of transmission coefficients $T_{\uparrow}(E)$ and $T_{\downarrow}(E)$ as a function of the incident energy for spin-up and spin-down carriers respectively. The red curve is for GaMnAs with 10 nm thickness. The spin-up carriers see a potential barrier V_0 caused by the magnetization of the GaMnAs layer. For incident energies $E < V_0$, the spin-up carrier wavefunction is evanescent in the GaMnAs layer and the transmission is suppressed. For $E > V_0$, stationary waves exist above the barrier and resonances occur in $T_{\uparrow}(E)$. Fig.5 manifests the suppression of the transmis-

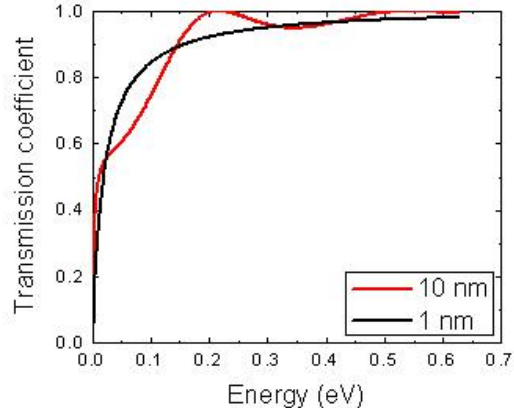


FIG. 6: Transmission coefficient as function of incident energy for spin-down carriers at zero temperature. The red curve is for GaMnAs thickness 10 nm; the black curve is 1 nm.

sion for $E < 0.21$ eV and many resonances for $E > 0.21$ eV.

The spin-down carriers traversing a potential well $-V_0$. Unlike the spin-up ones, the spin-down carriers are always able to tunnel through the GaMnAs layer since there is no barrier to block carriers tunneling. This can be seen in Fig.6. The spin-down carriers begin to tunnel at $E = 0$ eV while the spin-up ones at $E \approx V_0 = 0.21\text{eV}$. We also observe, from Fig. 5 and Fig.6, the transmission behaviors are different for spin-up and spin-down carriers. The transmission is indeed spin dependent as we proposed. A spin-polarized current is expected and will be discussed in Sec. III D.

Both Fig. 5 and Fig.6 show 100% transmission peaks. These peaks are actually quantum resonances corresponding to an integer number n of half wavelengths $\lambda/2$ fitting within the potential width, i.e. $d = n\lambda/2$ (Fabry-Perot-like interferences) [9, 16]. λ can be calculated by:

$$\lambda = \frac{2\pi}{k} = \frac{2\pi\hbar}{\sqrt{2m(E - V_0)}} \quad (22)$$

A plot of the transmission coefficient versus $\frac{d}{\lambda/2}$ is shown in Fig.7 and Fig.8. The peaks are located exactly at integer positions. The quantum resonances can also be seen in the Fig.9 and Fig.10. The resonance peaks located at integer times of a thickness interval. Such quantum resonances can be understood as mixings between itinerant states and bound states.

The resonance behaviors can be compared to the situation when the thickness of the GaMnAs layer is very small so that a sizable amount of carriers are able to tunnel through it. This is shown as the black curve in Fig.5 and Fig.6, which correspond to the transmission coefficient for thickness of GaMnAs 1 nm. The carriers begin to tunnel at $E = 0$ eV, no matter they are spin-up or spin-down. It might be expected that the smaller

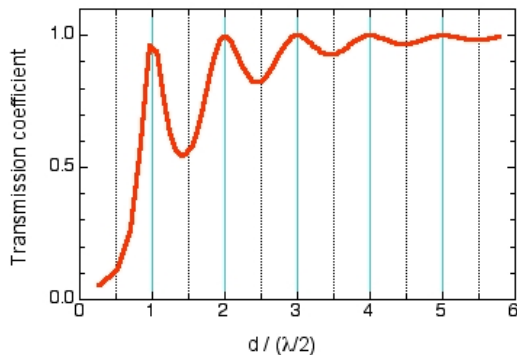


FIG. 7: Transmission coefficient as function of $\frac{d}{\lambda/2}$ for spin-up carriers at zero temperature. The 100% peaks are located exactly at integer positions.

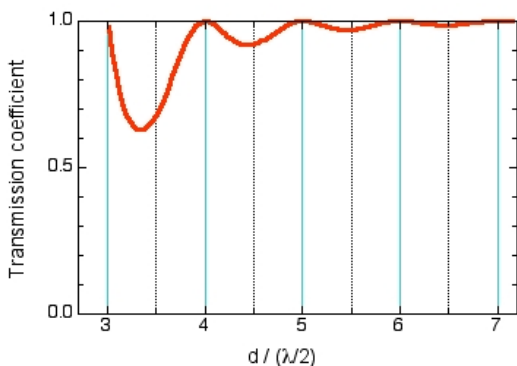


FIG. 8: Transmission coefficient as function of $\frac{d}{\lambda/2}$ for spin-down carriers at zero temperature. The 100% peaks are located exactly at integer positions.

the thickness the larger the transmission coefficient. It is true for most of the energy range. However in Fig.5 and Fig.6, T of the 1 nm curve is less than that of the 10 nm curve at some energies, which are resonance peak energies. The comparison infers that the quantum resonances enhance the transmission.

It is of application value since we can tune and achieve a high transmission just by tuning the incident energy with an applied voltage. In addition, the transmission as a function of E is spin-dependent, meaning that we can tune the polarization of transmission by tuning the incident energy as well.

D. Spin polarized current

A spin polarized current is our goal. Having the transmission coefficient, we are now able to calculate the current. The current is

$$j = evT \quad (23)$$

$$= e \frac{1}{\hbar} \frac{\partial E}{\partial k_l} T \quad (24)$$

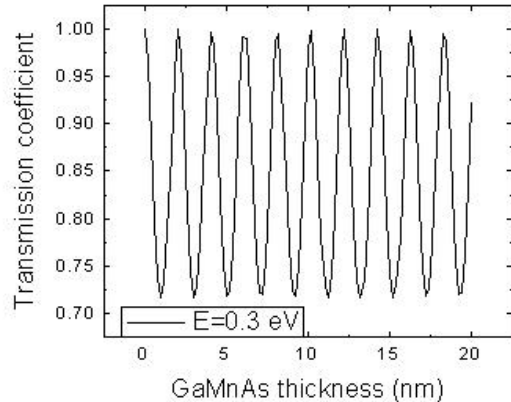


FIG. 9: Transmission coefficient as function of thickness at incident energy 0.3 eV for spin-up carriers at zero temperature.

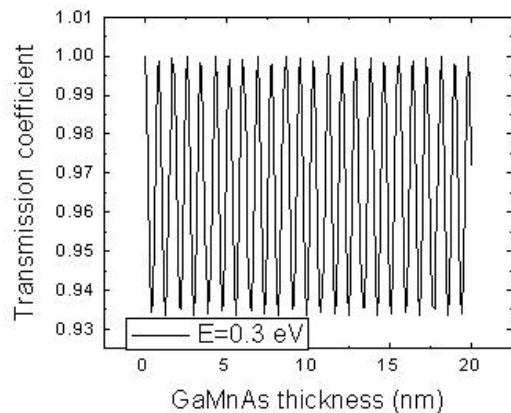


FIG. 10: Transmission coefficient as function of thickness at incident energy 0.3 eV for spin-down carriers at zero temperature.

The parabolic band, $E = \frac{\hbar^2 k^2}{2m^*}$, is used to calculate the derivative of energy. The current is then:

$$j = \frac{e\hbar k_F}{m^*} T \quad (25)$$

For different spin species, they have different transmission coefficient T_\uparrow, T_\downarrow , therefore causing different current j_\uparrow and j_\downarrow . The total current, assuming they have the same effective mass, is:

$$j = j_\uparrow + j_\downarrow \quad (26)$$

$$= \frac{e\hbar k_F}{m^*} T_\uparrow + \frac{e\hbar k_F}{m^*} T_\downarrow \quad (27)$$

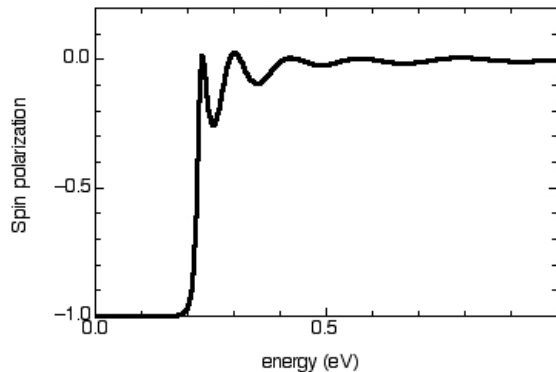


FIG. 11: Polarization as a function of incident energies. The polarization varies between -1 and 0 with different incident energies. Below around 0.2 eV, which is the potential barrier V_0 for spin-up holes, the current is fully polarized due to that only spin-down holes transmitted.

The polarization of current can be defined as:

$$P = \frac{j_{\uparrow} - j_{\downarrow}}{j} \quad (28)$$

$$= \frac{T_{\uparrow} - T_{\downarrow}}{T_{\uparrow} + T_{\downarrow}} \quad (29)$$

It is 0 for a non-polarized current and 1 or -1 for a fully polarized current. The transmission coefficients are different, depending on the spin orientation of holes with respect to that of Mn ions, as shown in our results, hence we achieve a spin-polarized current as we proposed. The result of polarization is in Fig.11. The polarization varies between -1 and 0 with different incident energies. Below around 0.2 eV, which is the potential barrier V_0 for spin-up holes, the current is fully polarized due to that only spin-down holes transmitted. Therefore we are able

to tune the spin polarization by tuning the incident energies, which might be useful in application. The temperature cause different splitting energy, as shown in Fig.4, and thus different transmission coefficients, making a different spin polarization. The polarization vanishes as temperature goes above the ferromagnetic transition temperature $T_c \approx 110\text{K}$.

IV. CONCLUSIONS

The spin-dependent transport in the heterostructure $p\text{-GaAs}/\text{GaMnAs}/p\text{-GaAs}$ is studied. The spin-up transmission is zero when its incident energy is less than the potential barrier $E < V_0$ and begins to tunnel when its energy goes up above the barrier $E > V_0$. The spin-down holes transmitted through the whole range of the incident energy, and have higher transmission coefficient T for higher incident energies. These can be understood as the results of tunneling through a potential barrier and well. Both of spin-up and spin-down transmission display an oscillatory behavior for increasing incident energy or GaMnAs layer width, i.e. the potential width. These features can be understood in terms of the quantum resonances.

It is of the most importance in this work that a spin polarized transmission, thus current, is achieved by this heterostructure $p\text{-GaAs}/\text{GaMnAs}/p\text{-GaAs}$. This can indeed be a possible devise of spin filters and would be applicable for spin-dependent optoelectronics. To be noted, the transmission rate as well as the spin polarization can be tuned by just tuning the incident energy, and achieve a high transmission rate with the enhancement from quantum resonances. Therefore it is of practical value to design a electronic devise based on this proposed heterostructure.

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