Long-range phase coherence in double-barrier magnetic tunnel junctions with a large thick metallic quantum well

Double-barrier magnetic tunnel junction (DBMTJ), where the quantum well (QW) can be formed in ultrathin magnetic film sandwiched by two parallel barrier and can be tuned by the thickness and the magnetic orientation of the middle layer and the, is an ideal model to study the discrete QW energy level, QW states and QW tunneling magnetoresistance (QW-TMR). It is also critical to develop kinds of novel spintronic devices based on QW-TMR and QW resonant tunneling diode. Thus, this topic has attracted much attention in magnetic research field.

In 2006, M02 group headed by Prof. Xiufeng Han, State Key Magnetic Laboratory, Institute of Physics, in collaboration with Prof. Xiaoguang Zhang from Oak Ridge National Laboratory and Prof. Zhongyi Lu from RENMIN University of China studied the QW states and QW resonant TMR by *ab-initio* calculation for the first time [*Y. Wang, Z. Y. Lu, X.-G. Zhang, and X. F. Han, First-principles theory of quantum well resonance in double barrier MTJs, Phys. Rev. Lett. 97 (2006) 087210*]. The calculation of density of states show that the QW states formed in majority Δ_1 band in middle Fe layer, which is confined by two MgO layers. The first principal calculation reveal the QW position as a function of thickness of Fe, which is in good agreement with phase accumulation model (PMA), and show the free electron character of the QW states. In addition, the Coulomb blockade effect appears when the middle Fe is not continuous and formed island. This work provides theoretical support for further study of QW resonant TMR in DBMTJ based MgO barrier and attracted much attention. However, it is very challengeable to fabricate high quality DBMTJ and the experimental results of QW are much weaker than theoretical prediction. Up to now, to preserve the phase coherence in QW, the QW states is only observed in ultrathin layer with thickness of 1~2 nm. In this case, it is impossible to modulate the Fermi level energy E_F by making a direct electrical connection with the middle QW layer. The decoherence process can be introduced by interface roughness or inelastic scattering in the QW and at the interface. To prevent the decoherence and realize the resonant tunneling in wide QW width, it is necessary to optimize the structure and material for DBMTJ.

Recently, experimental and theoretical study from M02 group and other international group show that the AB_2O_4 spinel oxide (such as $MgAl_2O_4$, $ZnAl_2O_4$, $SiMg_2O_4$, $SiZn_2O_4$) is a promising candidate for barrier material in MTJ, which show Δ_1 spin-filtering effect and small lattice mismatch with ferromagnetic electrode Fe, Co, FeCo alloy and half metal Heusler alloy, such as Co_2MnSi, Co_2FeAl, and large TMR has been predicted [*J. Zhang, X.-G. Zhang, and X. F. Han, Spinel oxides: Δ1 spin-filter barrier for a class of MTJs, Appl. Phys. Lett. 100 (2012) 222401*] What's more, both in-plane and perpendicular MTJ with $MgAl_2O_4$ barrier has been fabricated by sputtering method with CoFeB electrode and obtain the TMR ratio at low and room temperature [*B. S. Tao, D. L. Li, X. F. Han et al., Perpendicular magnetic anisotropy in Ta| $Co_{40}Fe_{40}B_{20}$| $MgAl_2O_4$ structures and perpendicular CoFeB|$MgAl_2O_4$| CoFeB MTJ, Appl. Phys. Lett. 105 (2014) 102407*].

Based on above research, in 2014, M02 group in collaboration with Dr. Yuan Lu from Institut Jean Lamour, France, developed the epitaxial DMTJ with core structure Fe(001)/ MgAlOx/ Fe(d)/ MgAlOx/ Fe by MBE system. The thickness of middle Fe layer is 6.3 nm, 7.5nm, and 12.6 nm, respectively. The oscillations of conductance as a function of bias have been observed in all the samples. The number of oscillations increase with increasing thickness of Fe and the position of the peaks are in good agreement with *ab-initio* calculation and PAM results, which confirm that the oscillations originate from the QW states in middle Fe layer. The long range phase coherence in such wide QW with is attributed to the perfect Fe/MgAlOx interface and high quality middle Fe film. The small lattice mismatch of Fe and MgAlOx induce small strain and few dislocations at the interface, which result in a small distribution of phase shift at the interface and enhance the QW resonant tunneling effect. Remarkably, up to ten separated QW resonance states were observed on MTJs with a 12 nm thick Fe QW from low to room temperature [*B. S. Tao, H. X. Yang,Y. L. Zuo, X. Devaux, G. Lengaigne, M. Hehn, D. Lacour, S. Andrieu, M. Chshiev, T. Hauet, F. Montaigne, S. Mangin, X. F. Han*, Y. Lu* , Long range phase coherence in DBMTJs with large thick metallic quantum well , Phys. Rev. Lett. 115 (2015) 157204*].

The above theoretical and experimental study provide important reference for further study and exploiting QW states and QW resonant TMR and achieving higher TMR ratio. This will promote the development of spintronic devices and application. Further research about this project is in process.

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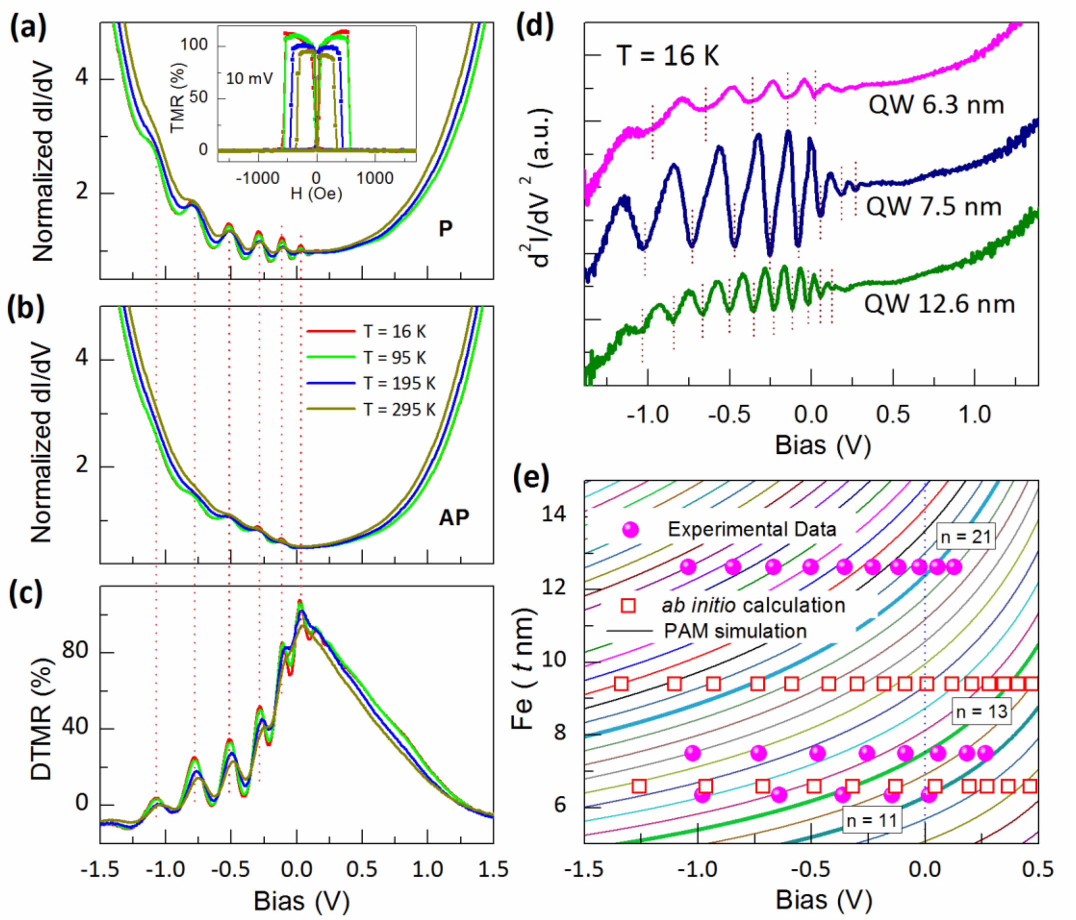

FIG. 1. Normalized conductance as a function of bias voltage in the (a) P and (b) AP state, respectively. (c) DTMR dependence with bias voltage. (d) QW thickness dependence of d^2I/dV^2 curves in the P state (measured at 16 K). The dashed lines indicate the resonant peak positions. (e)

QW peak positions for the experimental results (circles), PAM simulation results (lines), and *ab initio* calculation results (squares). The three numbers n in the figure represent the QW node number just below E_F for the three samples with different QW thickness.

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Abstract:
Double-barrier heterostructures are model systems for the study of electron tunneling and discrete energy levels in a quantum well (QW). Until now resonant tunneling phenomena in metallic QWs have been observed for limited thicknesses (1–2 nm) under which electron phase coherence is conserved. In the present study we show evidence of QW resonance states in Fe QWs up to 12 nm thick and at room temperature in fully epitaxial double MgAlOx barrier magnetic tunnel junctions. The electron phase coherence displayed in this QWs of unprecedented quality because of a homogenous interface phase shift due to the small lattice mismatch at the Fe-MgAlOx interface. The physical understanding of the critical role of interface strain on QW phase coherence will greatly promote the development of spin-dependent quantum resonant tunneling applications.