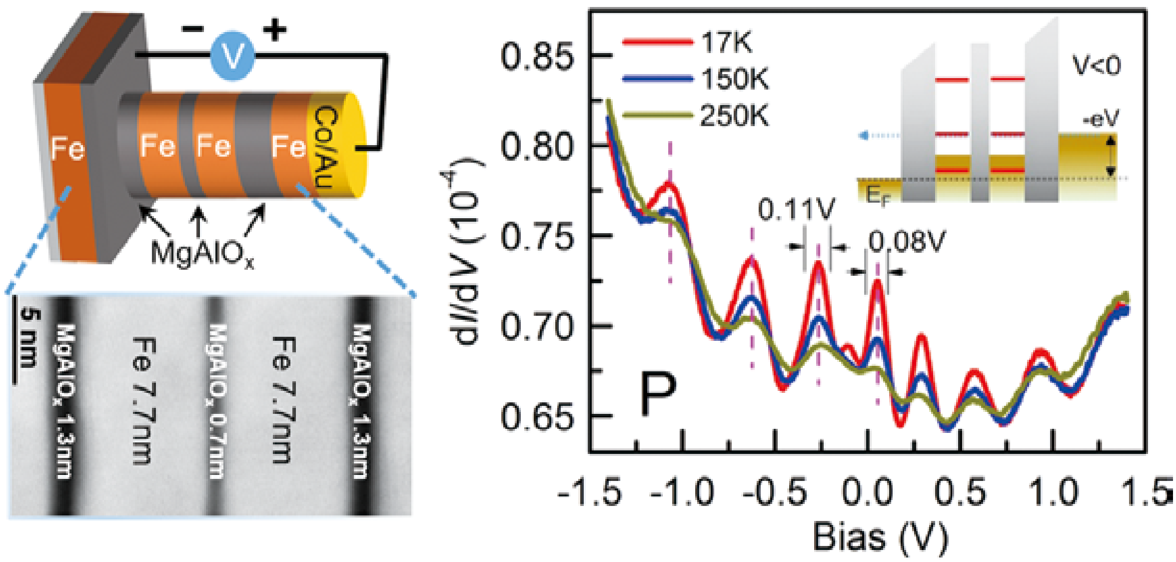
Coherent Resonant Tunneling through Double Metallic Quantum Well States

Due to its far-reaching scientific impact and broad applications, coherent resonant tunneling effect in magnetic tunnel junctions has aroused intensive interest from spintronic and semiconductor communities. Actually, resonant tunneling effect has been verified and utilized in semiconductor-based multi-quantum wells, such as resonant tunneling diode and light-emitting diodes with multiple quantum wells and *etc*. However, coherent resonant tunneling effect through metallic multi-quantum wells has been rarely reported and still a challenging topic till now, because of severe electron decoherence in metals. This coherent resonant tunneling is even more difficult for magnetic metal systems due to their shorter coherence lengths.

In 2005, a group led by Prof. HAN Xiufeng at the Institute of Physics (IOP) under the Chinese Academy of Sciences (CAS), in collaboration with Prof. ZHANG Xiaoguang at the Oak Ridge National Laboratory and Prof. LU Zhongyi at the Institute of Theoretical Physics, CAS utilized first principle calculation methods to quantitatively predict the quantum well and quantum well tunneling magnetoresistance (QW-TMR) effect for Fe(001)/MgO(001)/Fe(001)/MgO(001)/Fe(001) structures. Their results have shown (1) there exist hundreds of quantum well states in the Fe quantum well with the increase in its well thickness d; (2) the voltage dependence of the quantum well states; and (3) the giant QW-TMR effect induced by the quantum states. These results have remarkable impact on the development of spintronic devices based on the double barrier magnetic tunnel junctions and as-induced QW-TMR effect, due to which these results were published in *Physical Review Letters* [Y. Wang, Z. –Y. Lu, X. –G. Zhang* and X. F. Han*. *Phys. Rev. Lett*. 97 (2006) 087210].

In 2014, HAN's group, via cooperation with Dr. LU Yuan, Prof. S. Mangin and Prof. M. Hehn at the Université de Lorraine CNRS Institut Jean Lamour, elaborately designed and successfully grew epitaxial magnetic tunnel junctions with double $MgAl_2O_4$ single-crystalline barriers. The core structure of the design is Fe(001)/$MgAlO_x$/Fe(*d*)/$MgAlO_x$/Fe. As the thickness of the middle Fe (d) is 6.3nm, 7.5nm and 12.6nm, clear oscillation in differential conductance as a function of applied bias is unambiguously observed, confirming formation of quantum well states between the $MgAlO_x$ barriers. The quantum oscillation can still be observable in such thick iron films because of very tiny lattice mismatch between iron and $MgAlO_x$ barrier and epitaxial growth of the whole stacks. In this case, interfacial strains and defects are minimized, and phase decoherence introduced by interfacial scattering is reduced as well. Electrons can maintain their phase coherence through a long distance and strong oscillation is thus naturally achieved even at room temperatures. Due to the importance of realizing quantum well states in double barrier magnetic tunnel junctions at room temperatures, this work has been published in *Physical Review Letters* [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*, *Phys. Rev. Lett.* 115 (2015) 157204]. Based on this pioneering work, Prof. HAN and his cooperators further try to realize coherent resonant tunneling effect between different quantum well states such as double quantum wells.

As the first step in their further investigation, stacks of Fe/$MgAlO_x$(3 MLs)/Fe(9 nm)/$MgAlO_x$(6 MLs)/Fe(9 nm)/ $MgAlO_x$(3 MLs)/Fe with three barriers are epitaxially grown to form two quantum wells. Because the bottom and the top barriers are much thinner than the middle one, the applied bias dominantly drops on the middle barrier and



Left panel: Schematic diagram and high resolution STEM images of magnetic tunnel junctions with three barriers Fe/MgAlO$_x$(6 MLs)/Fe(7.7 nm)/MgAlO$_x$(3 MLs)/Fe(7.7 nm)/MgAlO$_x$(6 MLs)/Fe. Right panel: conductance oscillation under positive and negative biases. Inset shows schematics how electrons coherently and resonantly tunnel through two quantum wells at the same energy level.

Fermi levels of the two quantum wells are thus pinned by the Fermi level of the two outer electrodes. In this case, no matter positive or negative bias is applied, only states in one quantum well can be scanned. In the experiment, as a result, symmetrical conductance oscillation under both positive and negative biases is observed as expected, which confirms formation of double quantum wells with nearly equal energy spacing.

In order to realize coherent resonant tunneling between the quantum wells, other three rigid conditions should be fulfilled. (1) Quantum wells should have the same thickness to make well states have the same energy spacing. (2) Fermi levels of quantum wells cannot be pinned by electrodes to make these well states accessible by scanning bias. (3) Voltage dropped on the middle barrier should be as small as possible to make corresponding states from the two quantum wells keep similar energies. To satisfy the above requirements, the following stacks are grown: Fe/ MgAlO$_x$(6 MLs)/Fe(7.7 nm)/MgAlO$_x$(3 MLs)/Fe(7.7 nm)/MgAlO$_x$(6 MLs)/Fe. In this sample, conductance oscillation can also be successfully observed under positive and negative biases. By comparing observed peak positions and numbers with estimated counterparts from phase accumulation model, the researchers can safely argue that electrons coherently and resonantly tunnel through well states with the same energy and from the two quantum wells simultaneously. Furthermore, the oscillation peak in the double well sample is one half the width of those in single well samples, confirming the coherent and resonant tunneling effect.

This work reports coherently resonant tunneling between double well magnetic tunnel junctions for the first time, setting a solid experimental base for developing novel spintronic devices making use of resonant tunneling effects. This work has been published in *Nano Letters*. [B. S. Tao, C. H. Wan, P. Tang, J. F. Feng, H. X. Wei, X. Wang, S. Andrieu, H. X. Yang, M. Chshiev, X. Devaux, T. Hauet, F. Montaigne, S. Mangin, M. Hehn, D. Lacour, X. F. Han, Y. Lu. Coherent Resonant Tunneling through Double Metallic Quantum Well States. *Nano Lett*. 19 (2019) 3019–3026].

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Contact:

Institute of Physics, CAS
Dr. HAN Xiufeng
xfhan@iphy.ac.cn