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Resonant tunneling magnetoresistance in antiferromagnetically coupled Fe-based structures with multilayered Si/Ge spacers

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We report on the experimental evidence of the tunneling magnetoresistance (TMR) effect near 3% and its inversion in strongly antiferromagnetically coupled Fe(001)/([Si(0.2 nm)/Ge(0.2 nm)]*5)/Fe epitaxial structures with diffused interfaces. We explain the inversion of TMR with biasing voltage by resonant tunneling across impurity states with weak spin split $\Delta E \sim 10$ meV and spin-dependent filtering in the spacer layer. The resonant tunneling is manifested in spin-dependent resonances close to zero biasing voltages related to antiferromagnetic coupling across impurity states. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2198812]

Antiferromagnetic (AF) coupling between ferromagnetic (FM) layers separated by thin metallic spacers[1,2] can be strongly enhanced due to the formation of quantum well states and resonant electron confinement for one of spin channels.[3]

The AF coupling had been also predicted across tunneling barriers (TBs) with exchange via direct tunneling.[4] For TBs an exponential decrease of the coupling strength with thickness t of spacer layer and its negative temperature coefficient are expected.[2,4]

Our recent experiments showed that epitaxial Fe/Si/Fe structures demonstrate both strong AF coupling and tunneling.[5–7] This AF coupling is substantially stronger compared to metallic spacers and reaches a value of 5 mJ/m^2. The AF coupling decreases exponentially with t in a good accordance with the quantum interference model for insulating spacers.[2] We found a similar behavior of coupling for epitaxial structures with Si/Ge multilayered spacers.[8] For MgO (Ref. 9) and ZnSe (Ref. 10) spacers with sharper interfaces the insulating-type AF coupling is substantially smaller. Additionally, the free-electron model for exchange coupling via direct tunneling enables evaluation of the coupling strength only for weakly coupled structures[9] but fails to describe strong AF coupling in Fe/Si(Si/Ge)/Fe epitaxial structures.[11] Strongly coupled diffused structures show an increase of AF coupling with increase of temperature,[11] i.e., an opposite temperature coefficient compared to expectations from direct tunneling mechanism.[2,4] Thus, the direct tunneling mechanism fails to explain strong AF coupling and its positive temperature coefficient.

The alternative resonant model of AF coupling, which takes into account impurity resonant states in TB, predicts strongly enhanced coupling, its positive temperature coefficient,[12] and inversion of the TMR with biasing.[13] Resonant conditions for strongly AF coupled structures are fulfilled for biasing voltage $U_{\text{bias}} \sim 0$[12]. Below we demonstrate that our results are in accordance with the resonant model.

In order to study tunneling magnetoresistance (TMR) in our AF coupled structures we started with preparation of Fe(5 nm)/[(Si/Ge)$*N$]/Fe(3 nm) wedge-type multilayered structures with 0.2 nm thick Si and Ge sublayers using e-gun deposition as described elsewhere.[5–8]

We visualized distribution of stray fields in the direction normal to the film plane using superconducting quantum interference device (SQUID) microscope techniques[14] and found out that, in favor to pure Si spacers, Si/Ge spacers with multiple interfaces show more reproducible diffusion profile with sharp transitions between regions with different coupling. Figure 1 demonstrates that distribution of stray fields is inhomogeneous and changes dramatically with t. Close to interfaces for number of Si/Ge bilayers till $N=3$ we observe stray field characteristics for FM ordering, which transform abruptly to local inhomogeneities of stray fields. For $N>5$ stray fields are strongly reduced (Fig. 1). These data are in a good accordance with magnetic measurements,

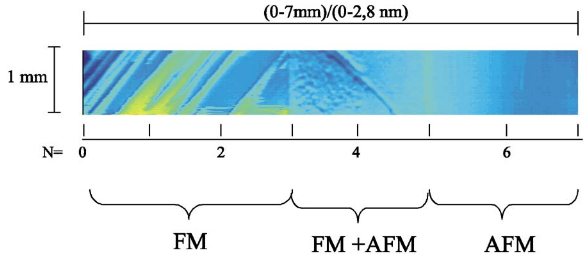

FIG. 1. (Color online) Distribution of stray fields in the direction normal to the film surface visualized from SQUID microscopy for Fe(5 nm)/[(Si(0.2 nm)/Ge(0.2 nm) *N]/Fe(3 nm) epitaxial wedge-type structure. Number N is the number of Si/Ge bilayers in the spacer with the thickness of each Si and Ge sublayer of 0.2 nm. The length of the sample of 7 mm corresponds to the thickness of spacer layer 2.8 nm. Distribution of stray fields corresponds to FM ordering ($N=1-3$), coexisting FM and AF ordering ($N=4,5$), and prevailing AF ordering ($N>5$).

[a)] Electronic mail: gareev.rashid@physik.uni-regensburg.de which demonstrate the transition from FM coupling to prevailing AF coupling after passing the region of comparable bilinear and biquadratic couplings.[8] The FM region transforms sharply to local ferromagnetic bridges. A concurrence between indirect AF coupling and direct FM coupling across bridges results in comparably strong AF and 90° (biquadratic) couplings. Thus, strong biquadratic coupling in our system is connected with FM bridges formed during interdiffusion. With increase of t, ferromagnetic bridges become broken and local magnetic impurities are formed in TB for $N=4,5$. A further increase of t leads to the separation of magnetic impurities by a TB, thus resulting in suppressed stray fields and prevailing AF coupling.[7]

After realizing controllable diffusion profile we prepared the structure with steplike t, number of bilayers $N=3,5,7$, and the same thickness of magnetic electrodes as for wedge-type structures. We used the patterning procedure as described in our previous work[7] and prepared two junctions for each t with the junction area $S=80\ \mu\text{m}^2$. Below we describe transport properties only for structures with $N=5$, for which we managed to observe TMR.

From measurements in current-perpendicular-to-plane (CPP) geometry we found that junctions with $N=5$ are highly resistive with resistance $R\sim 10\ \Omega$ at $T=4$ K and show similar transport behavior. We confirmed formation of TB from nonlinear I-V curves, and parabolic-type $dI/dV-V$ curves, which is a characteristic of an asymmetric TB (second Rowell criterion).[15] Brinkman fitting gives effective barrier height $\varphi(4\text{ K})\sim 0.5$ eV for effective thickness $t_{\text{eff}}\sim 2$ nm. Additionally, the moderate insulating-type decrease of zero-bias resistivity in the range of temperatures from $T=4$ K to $T=300$ K (third Rowell criterion), which does not exceed 50%, served as the robust confirmation of formation of TB. We note that $\varphi(4\text{ K})\cong\varphi(300\text{ K})$, additionally confirming formation of the pinhole-free TB.[15]

We performed our transport experiments in CPP geometry using lock-in techniques, thus testing the differential resistance $R_d=dU/dI$ and TMR at small biasing voltages (U_{bias}). The dependencies of $R_d(H)$ for different U_{bias} reveal the TMR effect close to zero bias, which reaches a value of $(R_{d\uparrow\downarrow}-R_{d\uparrow\uparrow})/R_{d\uparrow\uparrow}\sim 3\%$ at $T=4$ K (Fig. 2). The strongest TMR corresponds to $U_{\text{bias}}\sim -1$ mV. The TMR effect as well as the zero-bias anomaly show quick decrease with temperature, and for $T\sim 40$ K both effects are negligible. With increase of U_{bias} the TMR effect at $T=4$ K demonstrates inversion and changes sign to negative before it eliminates at small biasing voltages not exceeding tens of millivots. In contrast to expectations for resonant tunneling across states without spin splitting we observe two peaks of TMR with different sign at slightly different positive U_{bias}. The described behavior is a clear indication of the resonant character of TMR in our strongly AF coupled systems. The detailed TMR data taken at $T=4$ K with magnetic field applied along an easy axis are shown in Fig. 3. It is seen from the TMR data that the strength of AF coupling is similar for both resonances. We relate small values of TMR to resonant tunneling across multiple impurity channels, resulting in average in decreased values of TMR.[16] The saturation fields $H_{\text{sat}}\sim 4$ kOe obtained from TMR are in accordance with magneto-optical Kerr effect (MOKE) hysteresis data.

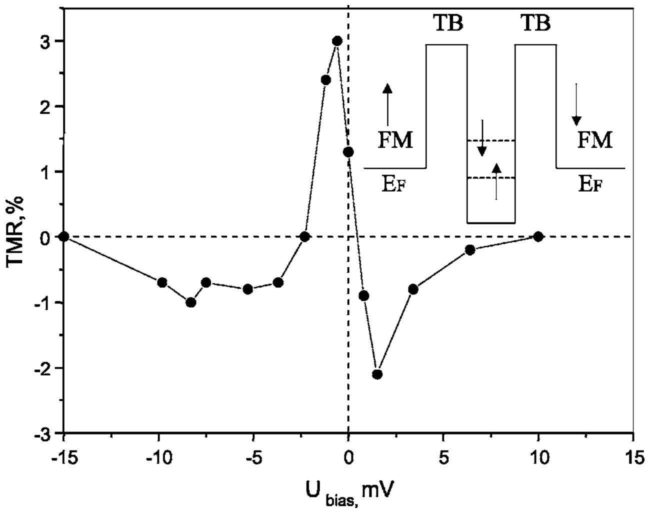

FIG. 2. TMR vs biasing voltage at $T=4$ K for Fe(5 nm)/[(Si(0.2 nm)/Ge(0.2 nm) *5]/Fe(3 nm) structure. TMR changes sign from positive to negative for both directions of biasing voltage. The inset shows the band diagram with spin-split resonant states inside TB close to the Fermi energy E_F.

The presence of two resonances we relate to spin-split impurity states inside the barrier, which can be formed asymmetrically, close to one of the interfaces. Resonant conditions are fulfilled at different biasing voltages for spin-up and spin-down channels where spin-split resonant states serve as effective spin filters. The majority channel is, accordingly, highly transparent close to zero bias, which results in a positive TMR. For higher biasing voltages the minority channel becomes prevailing, effective polarization changes sign and, thus, the inversion of TMR occurs. With a further increase of U_{bias} resonant conditions are no longer fulfilled, the system becomes decoupled for resonant channels and, thus, resonant TMR vanishes.

The dependence of differential resistivity on biasing voltage was calculated in Ref. 17 for resonant tunneling system with spin-split resonant states inside a TB. Our biasing dependence is in a good qualitative agreement with calculated curves for the case of spin-up impurity states with higher energies compared to spin-down states, where reso-

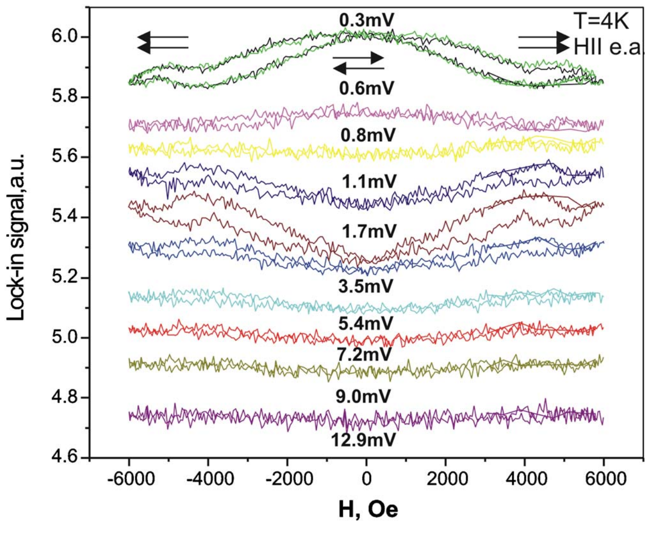

FIG. 3. (Color online) Dependence of the differential resistance dU/dI on magnetic field applied along an easy axis for different values of positive biasing voltage taken at temperature $T=4$ K. The junction area is $S=80\ \mu\text{m}^2$. Arrows indicate the relative alignment of magnetizations. The saturation field $H_{\text{sat}}\sim 4$ kOe corresponds to the strength of the exchange coupling $/J/\sim 1$ mJ/m^2.

nant levels are situated close to the Fermi energy.

The low spin splitting in our system ($\Delta E \sim 10$ meV) leads to thermoactivated mixing of resonant spin channels and, thus, quick decrease of the resonant TMR with temperature. We relate the small spin split to diffusive formation of iron-containing Si–Ge compounds with reduced exchange. The slight asymmetry of TMR can be connected with formation of different diffused interfaces. In contrast to reported earlier voltage-controlled magnetic spin filtering schemes (resonant tunneling diodes), which exploit an external magnetic field for spin splitting,[18] the spin-split resonant states are formed naturally inside our TBs.

We believe that strong AF coupling in studied structures is connected with AF exchange across local resonant states in accordance with mechanism described in Ref. 12. AF coupled structures with resonant channels can be useful for energy consuming voltage-regulated magnetic switches and logic elements.

Concluding, we observed the TMR effect in strongly AF coupled structures, which we connect with spin-split resonant states inside the tunneling barrier. The resonant character of tunneling combined with spin-filtering results in spin-dependent double resonances and inversion of the TMR effect. The experimental observation of spin-dependent resonances close to zero biasing voltages was related to AF coupling across impurity states.

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