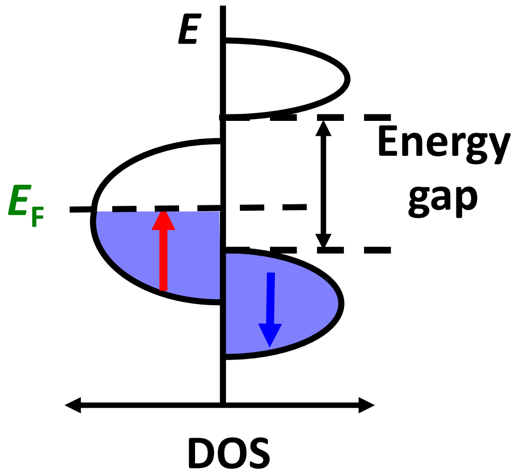
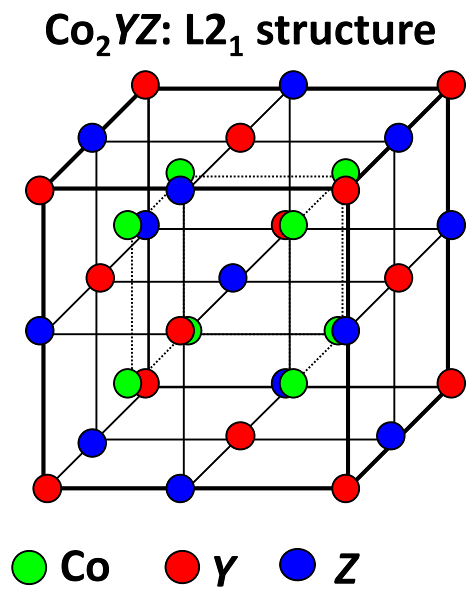
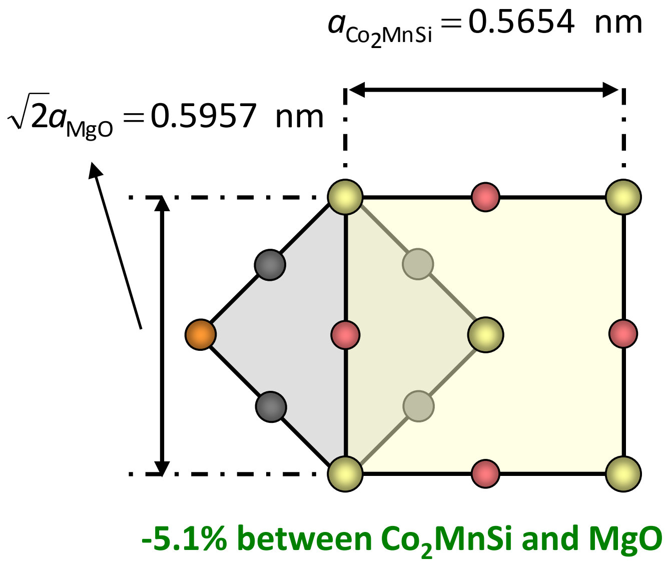
Magnetic tunnel junctions using Co-based Heusler alloy electrodes

Half-metallic Heusler alloy thin films for spintronic devices







(1) Half-metallic nature theoretically predicted for some of these alloys.
(2) High Curie temperatures well above RT.

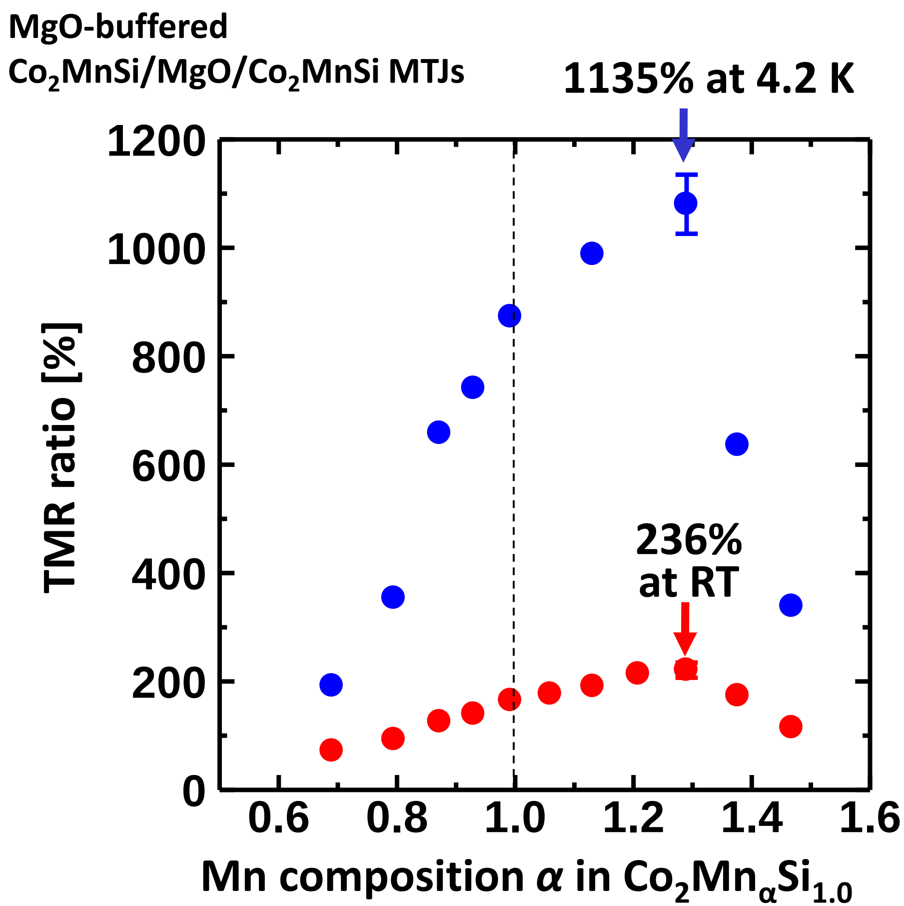
Consisting of four fcc sublattices

Coherent tunneling can be fully utilized in Heusler alloy/MgO heterostructures along with the half-metallicity

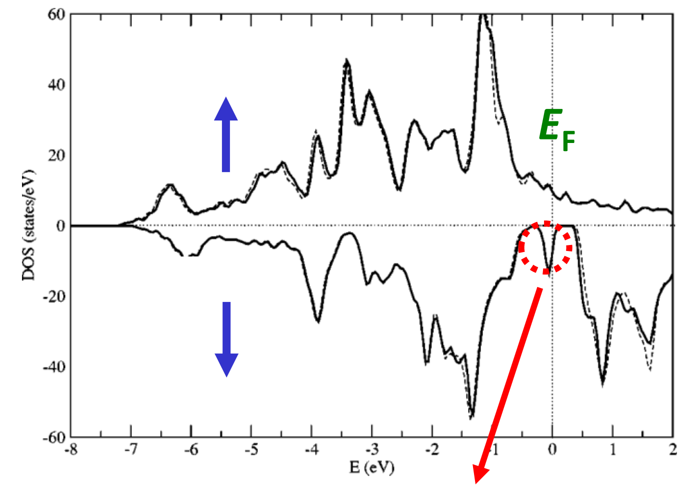
Purpose

To clarify the key factors that determine the spin-dependent tunneling characteristics of Heusler-alloy Co_2MnSi/MgO-based MTJs

The suppression of detrimental Co_{Mn} antisites is essential to obtain the half-metallicity of Co_2MnSi (CMS)



S.Picozzi et al., PRB 69, 094423 (2004).



Co_{Mn} antisites induce minority-spin gap states

1. The lower TMR ratios for MTJs with Mn-deficient CMS electrodes were explained by the formation of Co_{Mn} antisites that lead to minority-spin in-gap states around E_F as theoretically predicted by Picozzi et al.
2. Consistent with this, the higher TMR ratio for MTJs with Mn-rich CMS electrodes was explained by suppressed Co_{Mn} antisites.

(1) T. Ishikawa et al., APL 95, 232512 (2009). (2) M. Yamamoto et al., JPCM 22, 164212 (2010)

Formula unit composition model for nonstoichiometric Co_2MnSi

Assuming the antisite formation , not the vacant site formation

Formula unit composition

Mn-deficient $Co_2Mn_{0.69}Si_{1.0}$ $[Co_2][Mn_{0.75}Co_{0.17}Si_{0.08}][Si_{1.0}]$

Co_{Mn} antisite
(detrimental)

Mn-rich $Co_2Mn_{1.29}Si_{1.0}$ $[Co_{1.86}Mn_{0.14}][Mn][Si_{0.93}Mn_{0.07}]$

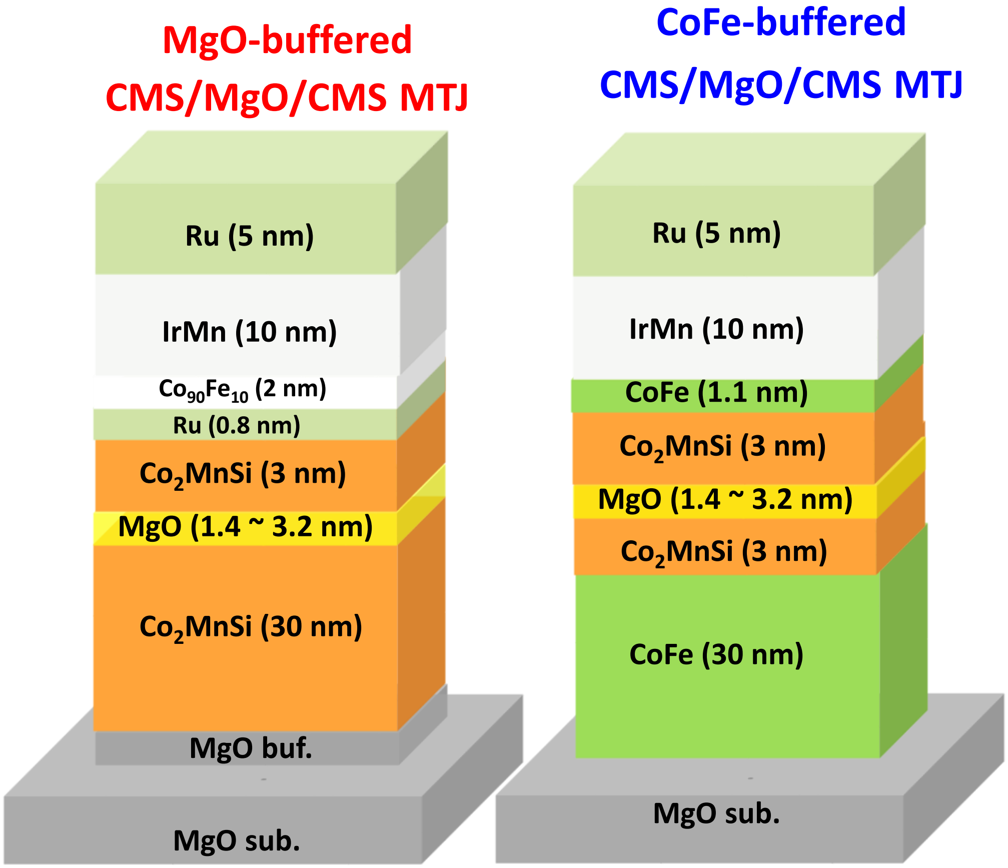
Mn_{Co} antisite
(not harmful)

M. Yamamoto et al., JPCM 22, 164212 (2010)

Enhancement of coherent tunneling contribution for Co_2MnSi/MgO MTJs

A CoFe-buffer and a thin Co_2MnSi lower electrode was introduced

Key points: (1) A smaller lattice misfit of -4.3% between CoFe and MgO
(2) The thin 3-nm-thick CMS lower electrode is lattice-matched to the CoFe buffer

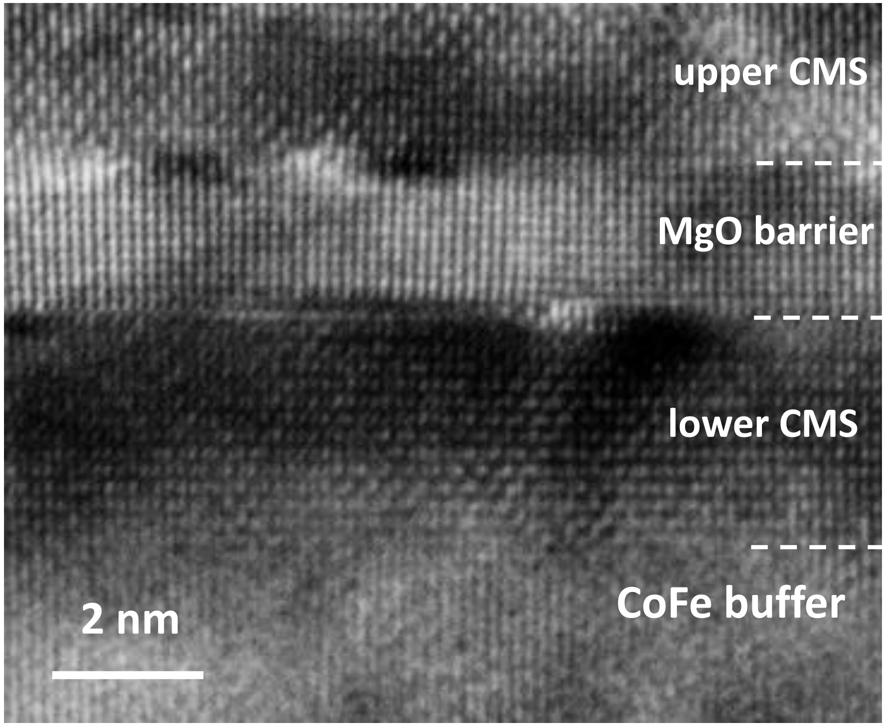


$Co_{2.0}Mn_{\alpha}Si_{0.96}$
α: 0.72 (Mn-deficient) ~ 1.57 (Mn-rich)

[1] H.-x. Liu *et al*, APL 101, 132418 (2012).

Fully epitaxial CoFe-buffered Co_2MnSi/MgO/Co_2MnSi MTJ layer structure

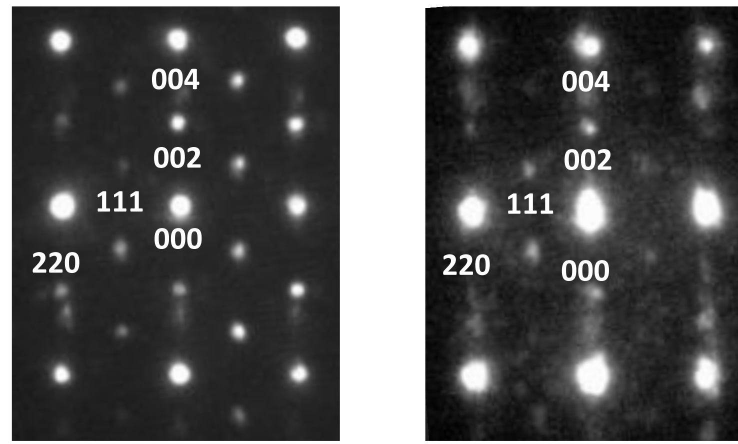
HRTEM lattice image



$Co_2Mn_{1.29}Si_{1.0}$

Electron beam diffraction

lower CMS **upper CMS**

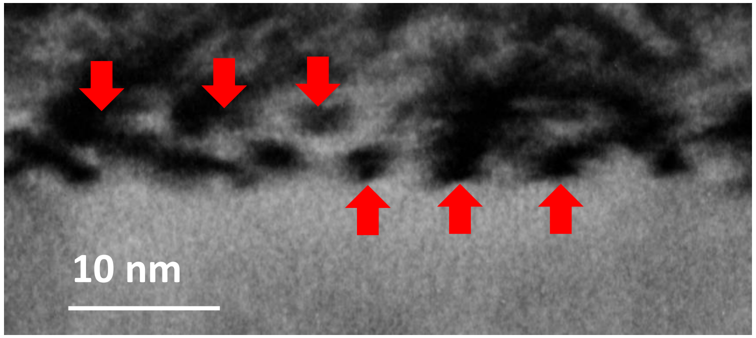


beam diameter: 2.5 nm

1. All layers were grown epitaxially and were single crystalline.
2. Atomically flat and abrupt interfaces were formed.
3. There were no clear lattice misfit dislocations between the CoFe buffer and the lower CMS electrode.
4. (111) spots for the upper CMS electrode were clearly observed.

Structural quality of the interfacial regions of the CoFe-buffered CMS MTJ was improved in terms of misfit dislocation density

Two-beam bright field TEM image



Misfit dislocation spacing at the lower and upper interfaces with a MgO

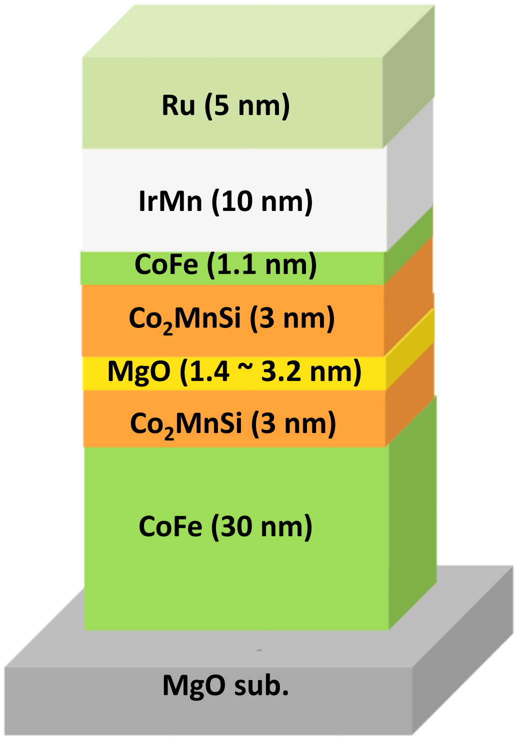
MTJ layer structure	Lower CMS/MgO (nm)	MgO/upper CMS (nm)
CoFe-buffered CMS MTJs	6.4 (1.0)	6.2 (1.4)
MgO-buffered CMS MTJs *	4.4 (0.8)	4.2 (0.7)

- T. M. Nakanati *et al*., JMMM 322 (2010) 357. Values in brackets are the standard deviations

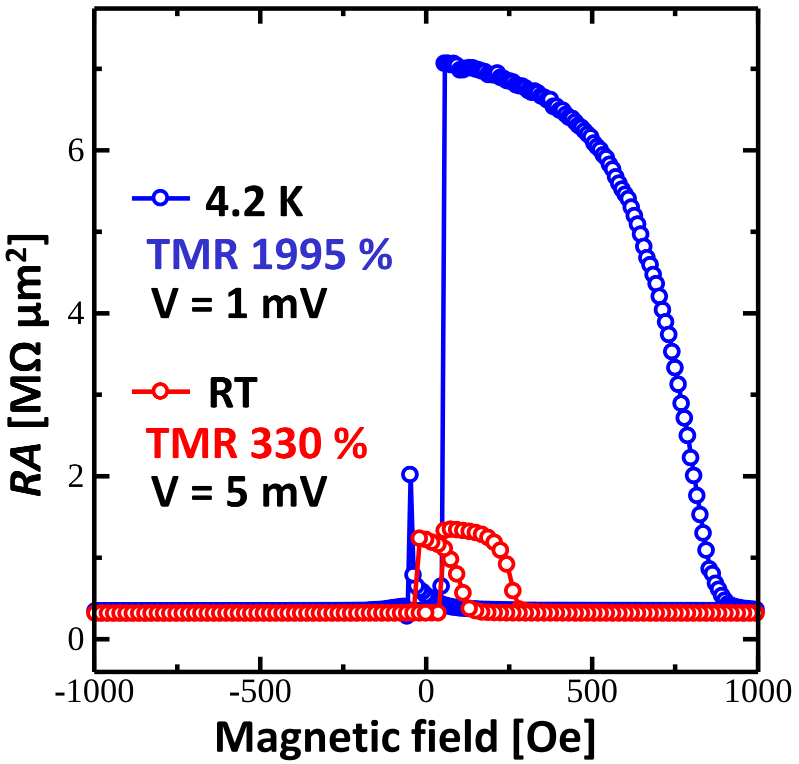
The CoFe-buffered Co_2MnSi MTJ layer structure showed larger misfit dislocation spacing, i.e., smaller density of misfit dislocation at the lower and upper MgO interfaces than the MgO-buffered Co_2MnSi MTJs.

Giant TMR ratios of 1995% at 4.2 K and 330% at RT were demonstrated

CoFe-buffered CMS/MgO/CMS MTJ

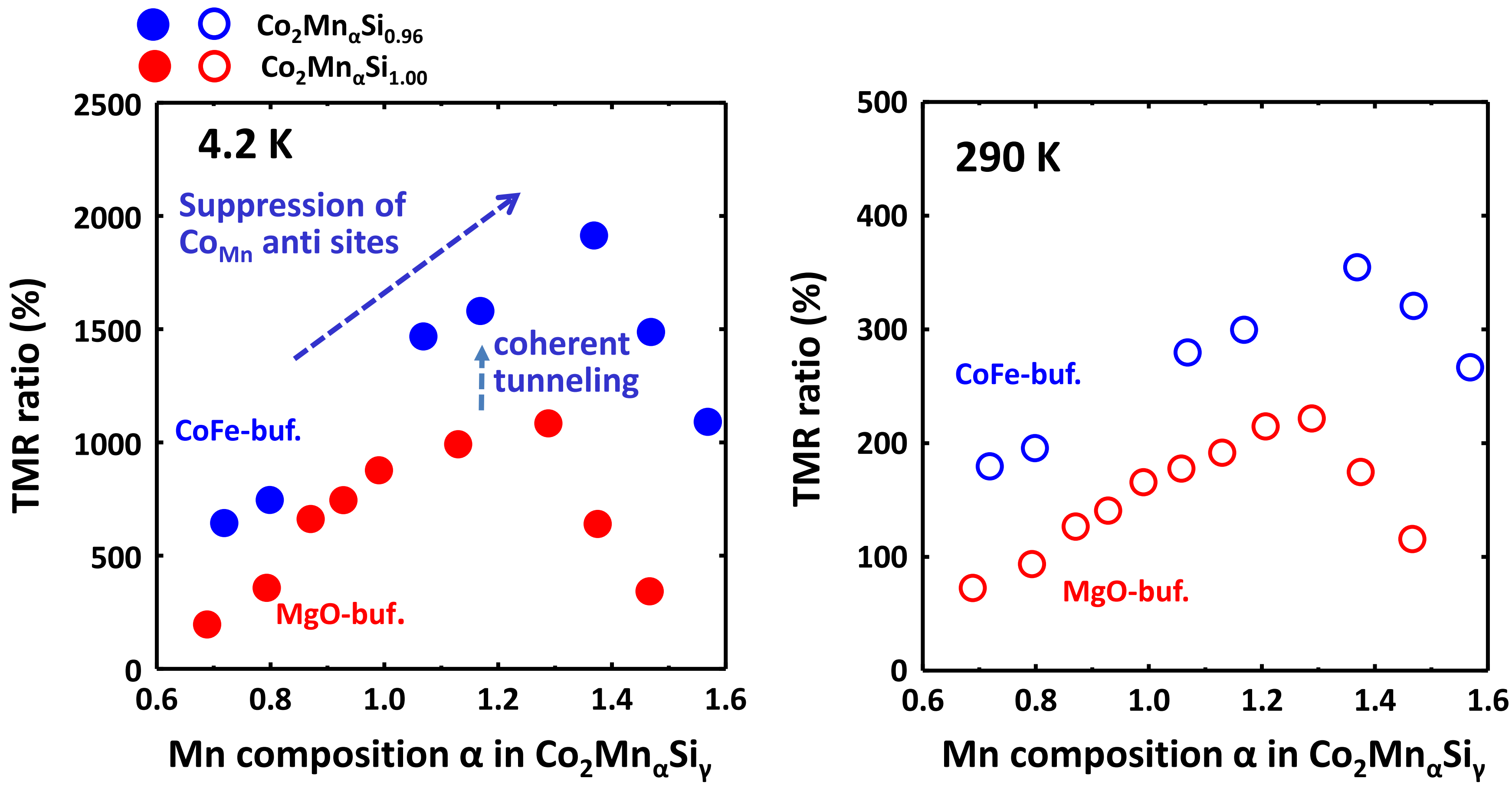


Intentionally Mn-rich $Co_2Mn_{1.35}Si_{0.88}$



1. These TMR ratios are much higher than the 1135% at 4.2 K and 236% at RT for MgO-buffered Co_2MnSi MTJs.
2. This can be attributed to enhanced coherent tunneling contribution arising from the increased misfit dislocation spacing.

Giant TMR ratios of up to 1995% at 4.2 K and up to 330% at RT were demonstrated, clearly indicating the half-metallicity of Co_2MnSi electrodes



The observed giant TMR ratios are due to:

1. **Enhanced half-metallicity obtained by the suppression of harmful Co_{Mn} antisites.**
2. **Enhanced coherent tunneling contribution evidenced by the comparison of the MgO-buffered and CoFe-buffered MTJs**

[1] H.-x. Liu *et al*, APL 101, 132418 (2012).

Conclusion

1. **The suppression of detrimental Co_{Mn} antisites is essential to obtain half-metallicity of Co_2MnSi. This can be achieved by using Mn-rich composition.**
2. **Giant TMR ratios of up to about 2000% at 4.2 K and up to 354% for $Co_2MnSi/MgO/Co_2MnSi$ clearly indicate the half-metallicity of Mn-rich Co_2MnSi electrodes.**