

SP-STM

Mn₃N₂ (010) showed:

1. magnetic corrugation superimposed on the normal non-magnetic signal
2. magnetic corrugation approximately 20-25% of the magnitude of the normal non-magnetic corrugation
3. bias-dependence of both the magnitude and sign of the magnetic corrugation
 - a. polarity of corrugation switches at a certain bias voltage
 - b. at all other bias voltages measured, the corrugation is non-zero
 - c. explanation of this behavior non-trivial and required full theoretical treatment. For full discussion, please see:

[Recent Advances in Atomic-Scale Spin-Polarized Scanning Tunneling Microscopy](#), Arthur R. Smith, Rong Yang, Haiqiang Yang, Alexey Dick, Joerg Neugebauer, Walter R. L. Lambrecht, *Microscopy Res. & Tech.* **66(2-3)**, 72 (2005).

[Atomic-Scale Spin-Polarized Scanning Tunneling Microscopy and Atomic Force Microscopy: a Review](#), Arthur R. Smith, *Journal of Scanning Probe Microscopy* 1(1), 3 (2006).

[Energy-dependent contrast in atomic-scale spin-polarized scanning tunneling microscopy of Mn₃N₂\(010\): Experiment and first-principles theory](#), Rong Yang, Haiqiang Yang, Arthur R. Smith, Alexey Dick, and Joerg Neugebauer, *Phys. Rev. B* 74, 115409 (2006).

Item 3 above is seen in the images below:

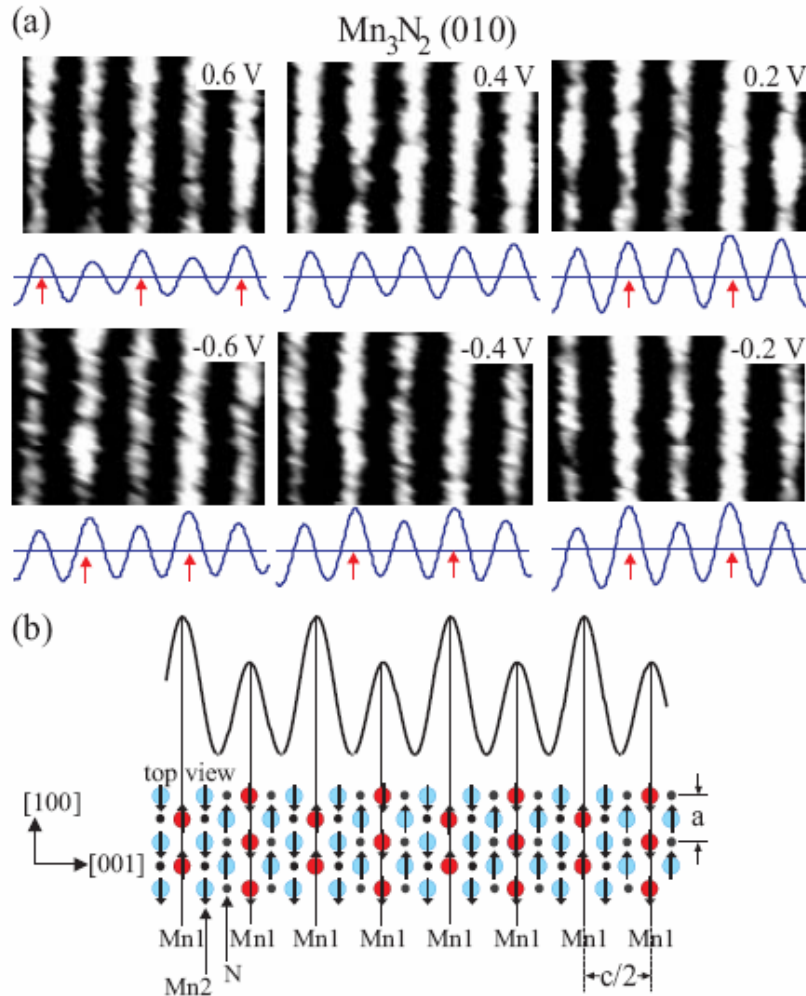
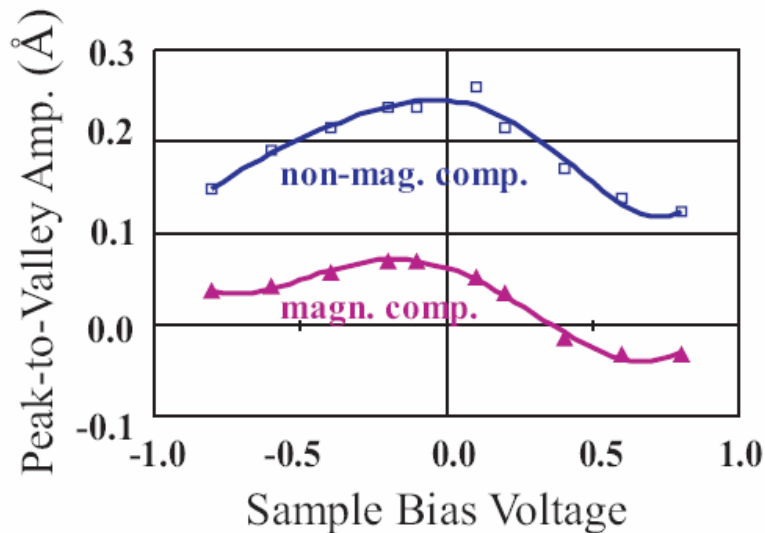


FIG. 4: (a) A series of SP-STM images of Mn₃N₂ (010) acquired using a Fe-coated W tip taken at the exact same surface location. The sample bias is indicated in each part, and tunnel current $I_t = 0.3$ nA. Height profiles below each image are averages over the vertical direction of the corresponding image; (b) diagram of spin-polarized STM line profile with atomic model of the Mn₃N₂ (010) surface, including magnetic moment vectors (Parts reprinted with permission of Wiley-Liss, Inc., a subsidiary of John Wiley and Sons, Inc., from A.R. Smith, R. Yang, H. Yang, A. Dick, J. Neugebauer, and W.R.L. Lambrecht, Recent Advances in Atomic-Scale Spin-Polarized Scanning Tunneling Microscopy, Microscopy Research and Technique 66, 72 (2005). Copyright 2005 WILEY-LISS, INC.).

[Atomic-Scale Spin-Polarized Scanning Tunneling Microscopy and Atomic Force Microscopy: a Review](#), Arthur R. Smith, Journal of Scanning Probe Microscopy 1(1), 3 (2006).

The magnitude with sign of the magnetic corrugation could be plotted as function of the bias voltage

It is found to vary smoothly and continuously over the range of bias voltage measured



[Atomic-Scale Spin-Polarized Scanning Tunneling Microscopy and Atomic Force Microscopy: a Review](#), Arthur R. Smith, Journal of Scanning Probe Microscopy 1(1), 3 (2006).

The full explanation of this bias-dependent behavior was finally explained in the following paper:

[Energy-dependent contrast in atomic-scale spin-polarized scanning tunneling microscopy of Mn₃N₂\(010\): Experiment and first-principles theory](#), Rong Yang, Haiqiang Yang, Arthur R. Smith, Alexey Dick, and Joerg Neugebauer, Phys. Rev. B 74, 115409 (2006).

In this paper, it was determined using first-principles theory calculations, that the bias-dependence could be completely explained in terms of the properties of the sample, and not due to energy-dependent property of the tip (this is a very important conclusion)

Furthermore, it was shown in this paper, that the polarity reversal coincided with a transition from majority to minority spin-polarized states of the sample.

Mn₃N₂ (010) was **not** the first antiferromagnetic surface to be resolved in SP-STM.

Three other important examples, two of which predated Mn₃N₂ (010) papers, should be carefully considered:

1. *Observation of Vacuum Tunneling of Spin-Polarized Electrons with the Scanning Tunneling Microscope*, R. Wiesendanger and H.-J. Guntherodt, G. Guntherodt, R. J. Gambino, and R. Ruf, *Physical Review Letters* **65**(2), 247 (1990).
2. *Real-Space Imaging of Two-Dimensional Antiferromagnetism on the Atomic Scale*, S. Heinze, M. Bode, A. Kubetzka, O. Pietzsch, X. Nie, S. Blügel, and R. Wiesendanger, *Science* **288**, 1805 (2000).
3. *Revealing Antiferromagnetic Order of the Fe Monolayer on W(001): Spin-Polarized Scanning Tunneling Microscopy and First-Principles Calculations*, A. Kubetzka, P. Ferriani, M. Bode, S. Heinze, G. Bihlmayer, K. von Bergmann, O. Pietzsch, S. Blugel, and R. Wiesendanger, *Physical Review Letters* **94**, 087204 (2005).

The 1990 paper by Wiesendanger *et al.* was the first paper on SP-STM of an antiferromagnetic surface. It reported:

- a terrace and step surface of Cr(001) measured using a ferromagnetic CrO₂ tip.
- An alternation of the measured step heights between terraces. The value of the step height alternated between 2 different values
- An explanation in terms of the contribution to the tunneling current due to the spin-polarized effect
 - o Increment in the parallel case
 - o Decrement in the anti-parallel case

Cr(001) Surface imaged using CrO₂ tip, Wiesendanger 1990

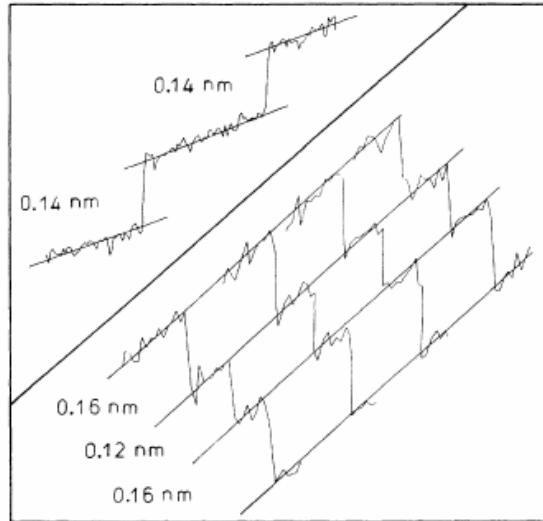


FIG. 3. Arbitrarily chosen (not successive) single-line scans over the same three monatomic steps taken from the STM image of Fig. 2(b), which was obtained with a CrO₂ tip. The same alternation of the step-height values (0.16, 0.12, and again 0.16 nm) in all single-line scans is evident. The line scans are 22 nm long. Inset: For comparison, a single-line scan over two monatomic steps taken from the STM image of Fig. 2(a), which was obtained with a tungsten tip. In this case, the measured step-height value is constant and corresponds to the topographic monatomic step height. This line scan is 70 nm long.

R. Wiesendanger and H.-J. Guntherodt, G. Guntherodt, R. J. Gambino, and R. Ruf,
Physical Review Letters **65**(2), 247 (1990).

The line scans were explained in terms of a model which was also presented in the same paper and credited to a different paper.

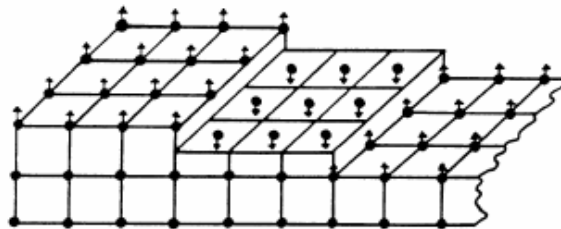


FIG. 1. Topological antiferromagnetic order of the Cr(001) surface with terraces separated by monatomic steps. Different terraces are magnetized in opposite directions. Only surface spins are indicated. (Figure taken from Ref. 7.)

shown in: R. Wiesendanger and H.-J. Guntherodt, G. Guntherodt, R. J. Gambino, and R. Ruf,
Physical Review Letters **65**(2), 247 (1990).

Ref.7 cited in caption is: S. Blugel, D. Pescia, and P. H. Dederichs, *Phys. Rev. B* **39**, 1392 (1989).

**Conceptual Picture to Explain the Step-height Alternation, Cr(001)
imaged with CrO2 tip, Wiesendanger et al., 1990**

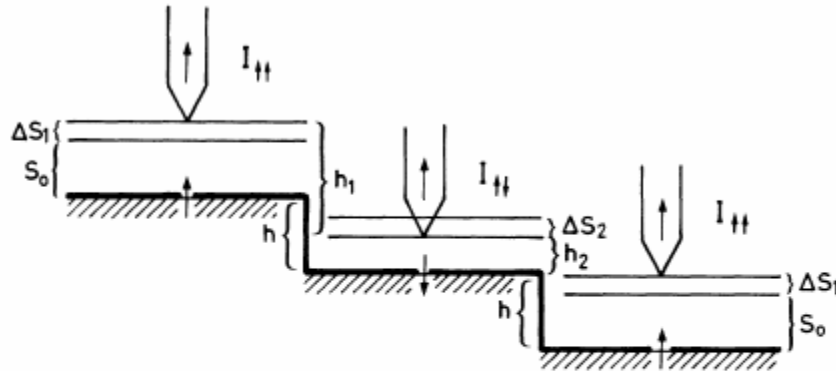


FIG. 4. Schematic drawing of a ferromagnetic tip scanning over alternately magnetized terraces separated by monatomic steps of height h . An additional contribution from SP tunneling leads to alternating step heights $h_1 = h + \Delta s_1 + \Delta s_2$ and $h_2 = h - \Delta s_1 - \Delta s_2$.

R. Wiesendanger and H.-J. Guntherodt, G. Guntherodt, R. J. Gambino, and R. Ruf, *Physical Review Letters* **65**(2), 247 (1990).

Wiesendanger *et al.* also presented some basic equations in order to explain the data:

Beginning with the following expressions:

$$I_{\uparrow\uparrow} = I_0(1 + P) \quad \text{and} \quad I_{\uparrow\downarrow} = I_0(1 - P)$$

P is called the ‘effective spin polarization of the tunneling junction’

P could be solved for to get:

$$P = \frac{I_{\uparrow\uparrow} - I_{\uparrow\downarrow}}{I_{\uparrow\uparrow} + I_{\uparrow\downarrow}}$$

from R. Wiesendanger and H.-J. Guntherodt, G. Guntherodt, R. J. Gambino, and R. Ruf, *Physical Review Letters* **65**(2), 247 (1990).

Then inserting exponential functions for the tunneling currents, expressions for the effective spin polarization were derived:

$$P = \frac{\exp(A\sqrt{\phi}\Delta s_1) - \exp(-A\sqrt{\phi}\Delta s_2)}{\exp(A\sqrt{\phi}\Delta s_1) + \exp(-A\sqrt{\phi}\Delta s_2)}$$
$$= \frac{\exp(A\sqrt{\phi}\Delta s) - 1}{\exp(A\sqrt{\phi}\Delta s) + 1} ,$$

from R. Wiesendanger and H.-J. Guntherodt, G. Guntherodt, R. J. Gambino, and R. Ruf, *Physical Review Letters* **65**(2), 247 (1990).

The authors measured Δs_1 and Δs_2 as well as ϕ

They used:

$$\Delta s = 0.02 \pm 0.01 \text{ nm}$$

and

$$4 \pm 0.5 \text{ eV for } \phi$$

to then calculate

$$P = (20 \pm 10)\%$$

The spin-polarized effect is superimposed on top of the non-magnetic image of the step-terrace structure. We can make the following conclusions:

- Clear evidence that the spin-polarized contribution can affect the total tunnel current
- Spin-polarized effect is only a small perturbation on top of the non-magnetic image
- Results consistent with the model of topological antiferromagnetism of Cr(001) proposed earlier by Blugel, Pescia, and Dederichs

The conclusion regarding the strength of the magnetic signal in comparison with the non-magnetic signal seemed natural at the time and for many years after 1990; this conclusion would not hold in all systems, as shown in the paper by Heinze *et al.* in 2000.