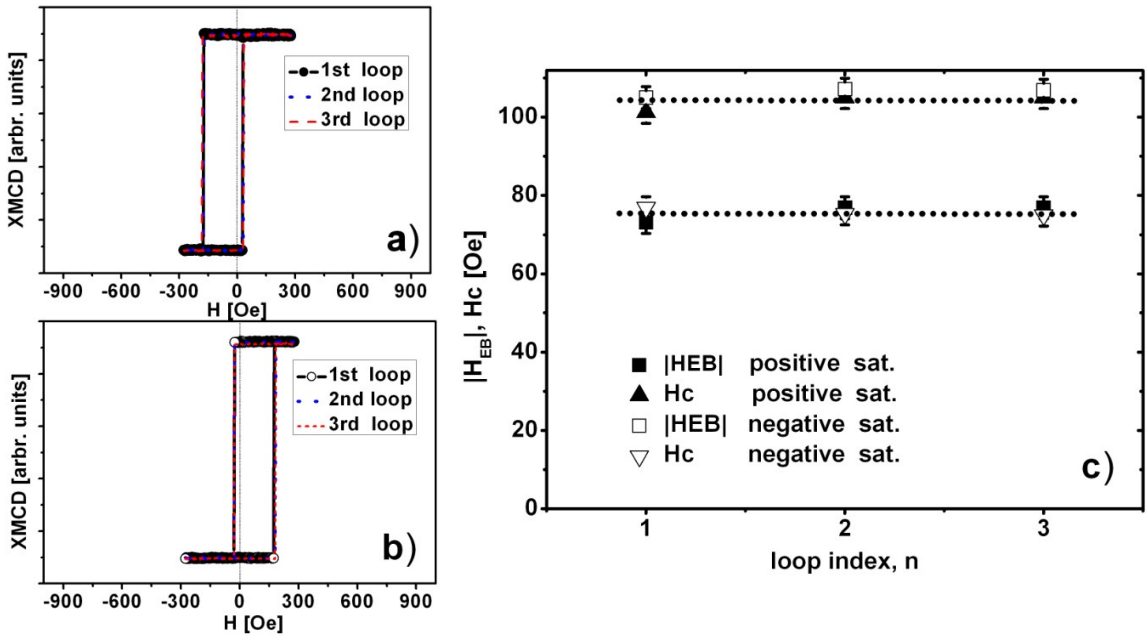
SUPPLEMENTARY INFORMATION

Supplementary Figures



Supplementary Figure S1 Training effect. In panel a) and b) we show hysteresis loops measured for single magnetic domain states of $DyCo_5$ layer of the FeGd/Ta(5 Å)/$DyCo_5$ sample. The first three hysteresis loops in panel a) were measured after applying a +3 kOe field, perpendicular to the sample. The magnetic field was swept three times from +300 Oe to –300 Oe and back to +300 Oe. The first three hysteresis loops in panel b) were measured after applying a -3 kOe field perpendicular to the sample and by sweeping (three times) the magnetic field from -300 Oe to +300 Oe and back to -300 Oe. In panel c) we show the coercive and the exchange bias fields for both scenarios and as a function of loop index. These data demonstrate the robust character of the exchange bias effect in our samples. The error bars are equal to 2.8 Oe.

Supplementary Methods

Test for the training effect. The training effect refers to the dramatic change of the hysteresis loop of the pinned layer, measured consecutively right after setting in an unidirectional anisotropy. Generally, both the coercive and the exchange bias fields decrease as a function of loop index. Also, upon training, the symmetry of the hysteresis loops may change due to a progressive variation of the magnetic domain/interface structure of the antiferromagnet. In F/AF bilayers the training effect is related to the metastability of the virgin magnetic state of the bulk and/or the magnetic state of the interface prepared by field cooling or field growth procedures. A drastic change of the AF magnetic domain state leads to a drastic change of the hysteresis loop. Also, in case of a rather stable AF domain structure, the magnetic frustration at the interface may evolve as a function of loop index, allowing the interfacial AF spins to change towards more favorable orientations. This also leads to a change of the hysteresis loops, characterized by a monotonic decrease of the exchange bias field[5]. For both cases, the largest change of the coercive and the exchange bias field occurs during the first two hysteresis cycles. Therefore, probing the occurrence of a training effect requires several initial loops.

In the Supplementary Figure S1 we have probed the training effect for the sample FeGd/Ta(5 Å)/$DyCo_5$. We have set the HFi in a single magnetic domain state and measured three SFi hysteresis loops in a consecutive manner. In a first scenario, we applied a positive magnetic field higher than the coercive field of the HFi layer, and measured three consecutive element specific minor loops which are characteristic for the biased SFi. The field was swept from positive to negative and back to positive fields. In a second scenario, we have saturated the HFi by a negative magnetic field, and measured three consecutive SFi hysteresis loops by sweeping the field from negative to positive and to negative again.

For both cases we observe rectangular shaped hysteresis loops, which exhibit negative exchange bias and increased coercivity with respect to the free SFi layer (compare to Figure 3e). We also observe that the hysteresis loops do not exhibit a dramatic change as a function of loop index. This can be seen also in Supplementary Figure S1c where the coercive and exchange bias fields exhibit a linear character (within the experimental uncertainty) as a function of loop index. This suggests that the induced unidirectional anisotropy in our films is most robust. One reason for this robustness is that the HFi exhibits a single domain state and a strong perpendicular uniaxial anisotropy. This, corroborated with the proximity to a non-magnetic (Ta) layer minimizes also a training effect which may be caused by the inherent interfacial magnetic disorder leading to frustrated spin configurations.