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SUPPLEMENTARY INFORMATION

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Creation and annihilation of non-volatile fixed magnetic skyrmions using voltage control of magnetic anisotropy

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Supplementary Information

Creation and annihilation of nonvolatile magnetic skyrmions using voltage control of magnetic anisotropy

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1. Detailed analysis of MFM profiles: To confirm that our spin structures are not classical bubbles, we simulated MFM profile of a classical bubble with 400 nm core diameter surrounded by a 300 nm domain wall separating the two oppositely polarized perpendicular regions (Fig. S1 (b)). We observe two side peaks that emerge due to the achiral domain wall with spins pointing in the same direction separating two perpendicular regions. We do not observe this in our MFM line scans (Fig. S1(c)). All the MFM line scans qualitatively match well with the simulated skyrmion MFM profile shown in Fig. S1(a).

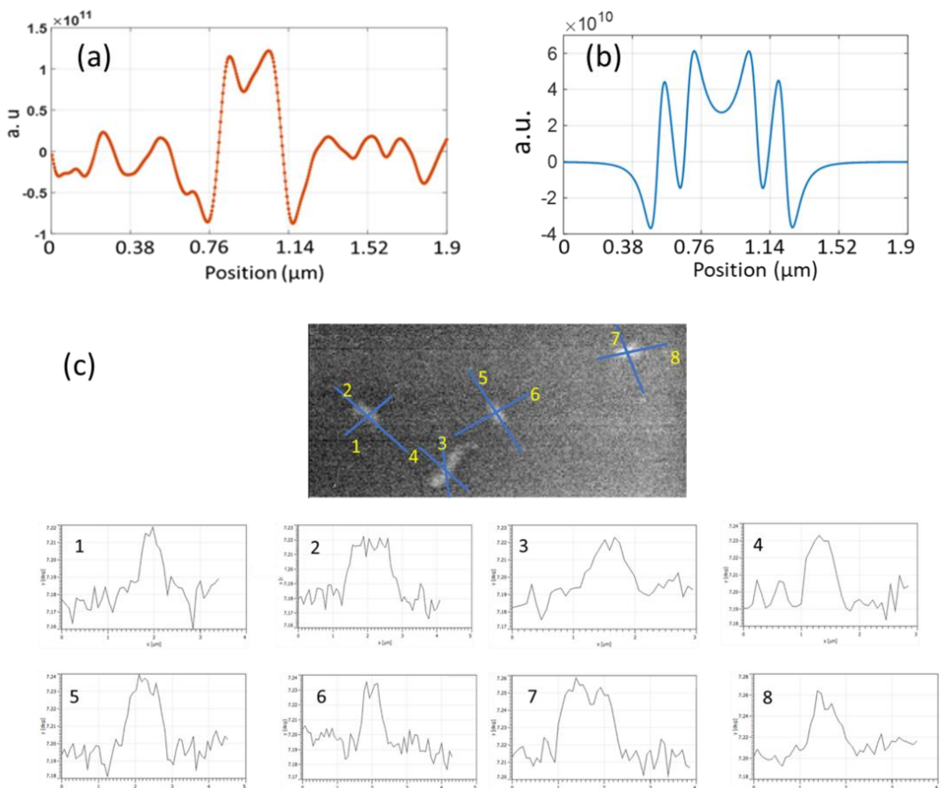

Figure S1. Simulated MFM profile of (a) a skyrmion, (b) Classical bubble, (c) Experimental MFM profiles of skyrmions (created after voltage application) match well with the simulated skyrmion profile but fundamentally different from a classical bubble.

2. Exchange bias and M_s dependence on gate voltage: In order to investigate the effect of the applied voltage on the exchange bias and magnetization saturation in our sample, we performed anomalous Hall effect measurements under different applied gate voltages as shown in Fig. S2. This measurement is performed on the sample with nominal CoFeB thickness of around 1.08 nm. We observe that the exchange bias under different bias voltages is almost the same and the negligible changes might be due to the change in interfacial properties. Furthermore, the difference in anomalous Hall resistance between the up/down states is independent of the applied voltage, which suggests that the magnetization saturation (M_s) does not change.

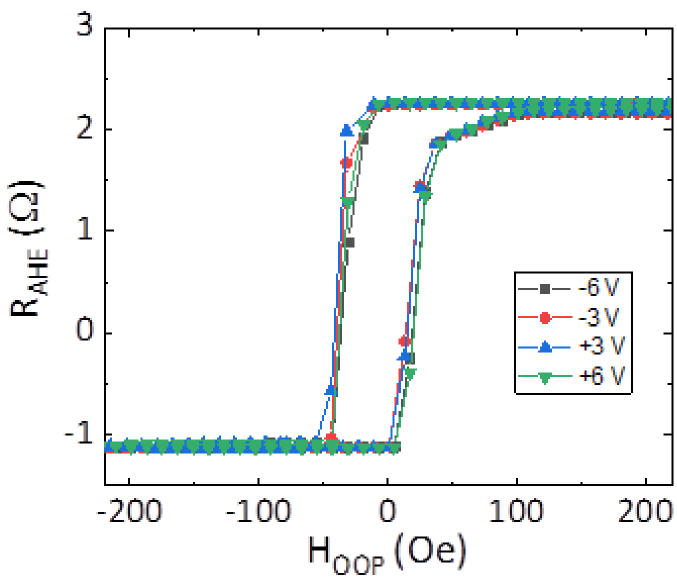

Figure S2. Anomalous Hall (AHE) measurement on a sample with CoFeB thickness of 1.08 nm and under different gate voltages. The exchange bias and the difference in AHE resistance between the two states is almost the same for all samples.

3. Emergence of skyrmion/stripe domains at the same location in different magnetization cycle:

We magnetized our sample several times by first applying a large saturation magnetic field and subsequently removing the field to observe the equilibrium magnetic states. We found skyrmions and stripe domains have a propensity to nucleate/form at the same location as shown in Fig. S3. This demonstrates that there is inhomogeneity (i.e. nucleation/pinning sites) across the device and due to that, skyrmions/chiral domain are created preferentially in these regions of the film. Moreover, the skyrmions that were created by electric field application were also present in the different magnetization cycles. This perhaps indicates that these are the most favorable sites for skyrmion/domain nucleation among all the possible nucleation/pinning sites. These positions are shown with arrows.

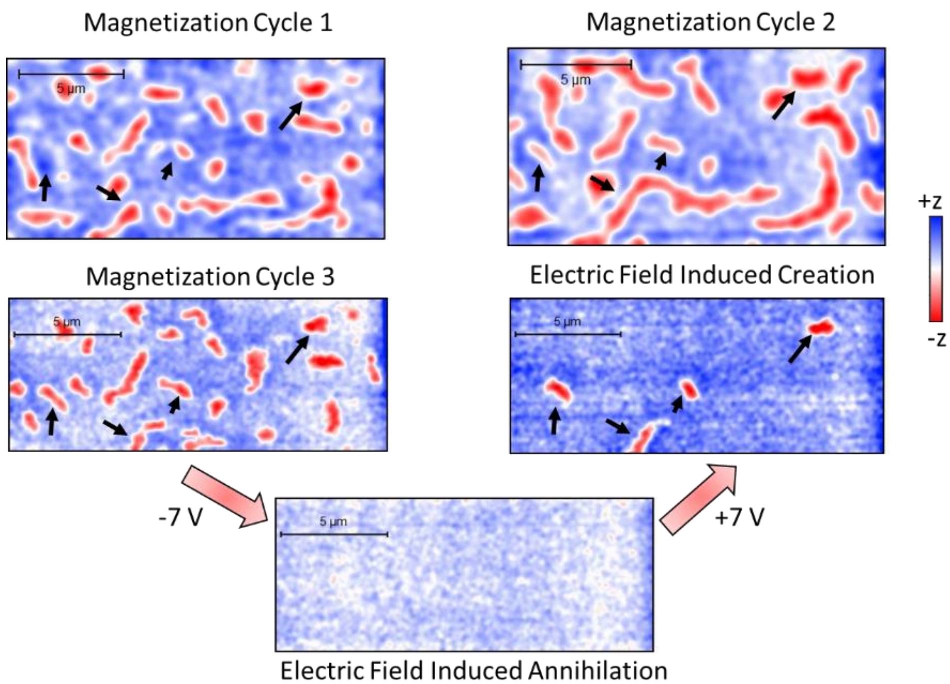

Figure S3. Skyrmions/stripe domains at almost exact position in different magnetization cycle and after electric field induced creation.

4. Up and Down Scan: To confirm there is no tip induced effects, we scanned the same area twice (scanning up and down). These two scans produced similar images as shown in Fig. S4 indicating that tip induced changes to the magnetic state of the films in minimal.

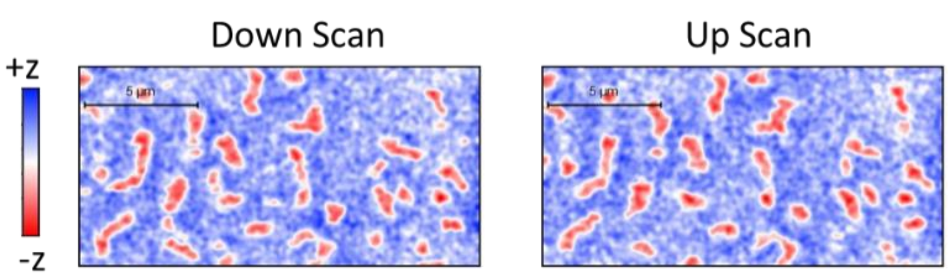

Figure S4. MFM image of the same location scanning up and down

5. Raw Images: Many of the magnetic force microscopy (MFM) images in the main paper and some in the supplement have been presented after performing some image processing. The raw MFM images that correspond to these processed images are presented below.

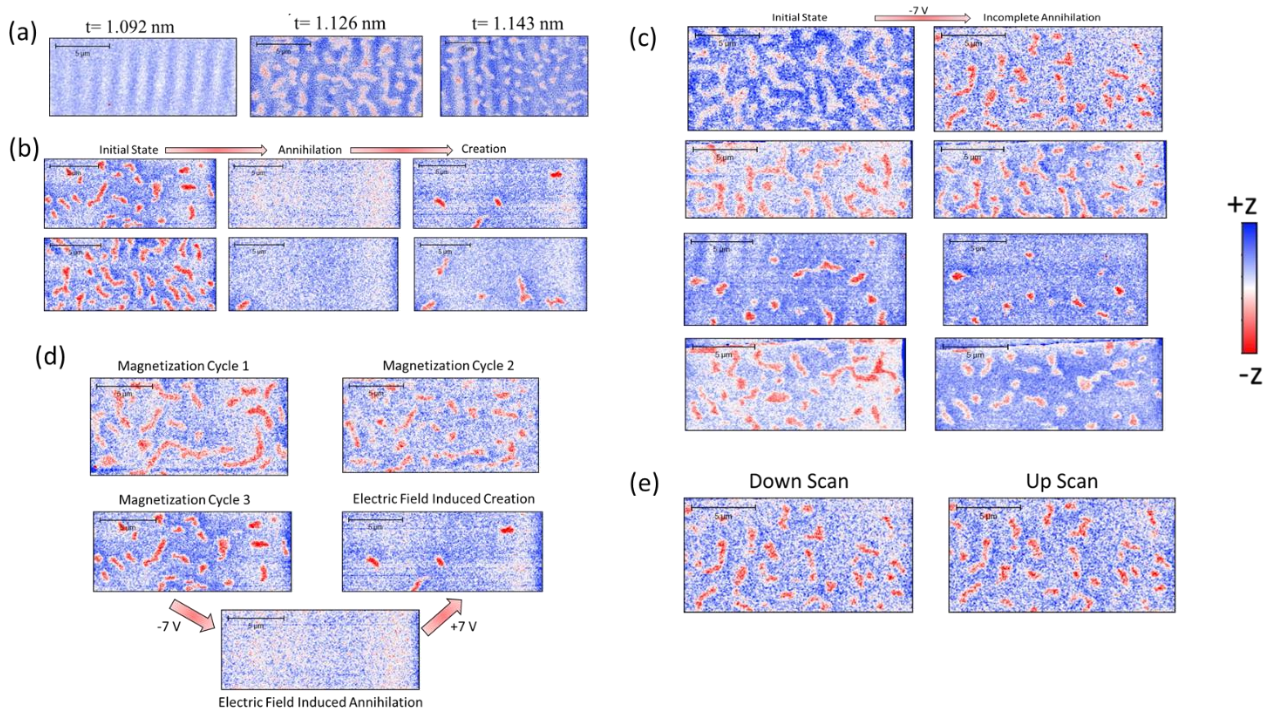

Figure S5. RAW MFM image corresponding to the following figures in the main or supplemental section: (a) Fig. 1(c), (b) Fig. 3(b), (c) Fig. 4, (d) Fig. S3, (e) Fig. S4.

6. Micromagnetic Code:

```
//Geometry
SetMesh(1000, 1000, 1, 3.8e-09, 3.8e-09, 1.1e-09, 0, 0, 0)
SetGeom(rect(3800e-9,3800e-9))

//Material Parameters
Aex = 8e-12
alpha = 0.01
anisU = vector(0, 0, 1)
Msat=9.3e5
Dind=0.000135
//Exchange Bias
B_ext=vector(0,0,0.0015)

//ThermalNoise
Temp=300
fixdt=8e-13
ThermSeed(125)

//Inhomogeneity
grainSize  := 100e-9
randomSeed := 123
maxRegion  := 255
```

```
ext_makegrains(grainSize, maxRegion, randomSeed)

ku:=5.8e5
for i:=0; i<maxRegion; i++{
j:=randnorm()
Ku1.SetRegion(i, ku+j*0.01*Ku)
}

//Initialization
m=randommag()
run (200e-9)

//Annihilate

for i:=0; i<maxRegion; i++{
Ku1.SetRegion(i, Ku1.getregion(i)+7e3)
}
run (200e-9)

for i:=0; i<maxRegion; i++{
Ku1.SetRegion(i, Ku1.getregion(i)-7e3)
}
run (100e-9)

//Create
for i:=0; i<maxRegion; i++{
Ku1.SetRegion(i, Ku1.getregion(i)-7e3)
}
run (200e-9)

for i:=0; i<maxRegion; i++{
Ku1.SetRegion(i, Ku1.getregion(i)+7e3)
}
run (200e-9)
```