Classification tasks using input driven nonlinear magnetization dynamics in spin Hall oscillator

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Supporting Materials

Supplementary material 1

Ferromagnetic resonance.

**Supplementary material 2**

Investigation of magnetization dynamics and 4-bit digit pattern separation on regular pulse scheme with I0 = 0, I1 = 4.0 & 6.0 mA, ∆t = 4 ns, = 3 ns.

**Supplementary material 3**

Investigation of magnetization dynamics and 4-bit digit pattern separation on regular pulse scheme with I0 = 0 mA, I1 = 3.5 mA, ∆t = 4 ns, = 1.5 ns & 3.6 ns.

**Supplementary material 4**

Magnetization dynamics of 16 combinations of 4-bit digit pattern separation on modified pulse scheme with Ie = 3.0 mA, δ = 5 ns, I0 = 1.2 mA, I1 = 2.4 mA, ∆t = 4 ns, = 3.0 ns.

**Supplementary material 5**

Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with Ie =1.4 mA, δ =5 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns.

**Supplementary material 6**

Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with Ie =5.0 mA, δ =5 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns.

**Supplementary material 7**

Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with Ie =5.0 mA, δ =1, 20 & 25 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns.

Supplementary material 1: Ferromagnetic resonance.



**Figure S1. a.** Simulated ferromagnetic resonance (FMR) for modelled spin Hall oscillator (SHO) in the main text. The applied magnetic field (Hext) is oriented along Y axis and the oscillating magnetic field (Hrf) at a fixed microwave frequency is applied along X axis with a strength of 1 mT.The Hext is sweeped for fixed frequency. **b.** The obtained resonant field () as a function of the applied frequency. The data are fitted with the Kittel equation yielding an effective magnetization, with gyromagnetic ratio .

**Supplementary material 2: Investigation of magnetization dynamics and 4-bit digit pattern separation on regular pulse scheme with I0 = 0, I1 = 4.0 & 6.0 mA, ∆t = 4 ns, = 3 ns.**

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**Figure S2.** Figures **a** and **d** show the 4-bit binary input pulse patterns with input parameters I0 = 0, I1 = 4.0 mA, ∆t = 4 ns and = 3 ns, for the 4-bit patterns 0101 and 1010 respectively. For both pattern 0101 and pattern 1010, the Mx oscillation amplitudes in the Figs. **b** and **e** corresponding to the input bit 1 are the same. This prevents the separation of the two patterns as can be seen from the similar value of FFT amplitude in Figs **c** and **f**. Figures **g** and **j** show the 4-bit binary input pulse with input parameters with I1 in the nonlinear regime I0 = 0, I1 = 6.0 mA, ∆t = 4 ns and = 3 ns, for the 4-bit patterns 0101 and 1010 respectively. For both pattern 0101 and pattern 1010, the Mx response is auto-oscillations as shown in the Figures **h** and **k,** wherebit 1 pulses oscillate at the same amplitude level. This again prevents the separation of the two patterns as seen from the similar value of FFT amplitude at the filtering frequency of 9.0 GHz as shown the Figs **i** and **l**.

**Supplementary material 3: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with I0 = 0 mA, I1 = 3.5 mA, ∆t = 4 ns, = 1.5 ns & 3.6 ns.**

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**Figure S3.** Figure. **a**(**d**) shows the 4-bit binary input pulse with input parameters I0 = 0, I1 = 3.5 mA, ∆t = 4 ns and = 1.5 ns (3.6ns), for the 4-bit pattern 1111. For = 1.5 ns (Fig. **b**), due to the relaxation of the excited small angle precession, Mx amplitudes corresponding to each of input bit 1 pulses are the same. However, for = 3.6 ns (Fig. **e**), the next bit 1 pulse arrives before the relaxation of the previously excited Mxprecession, leading to progressively increasing amplitudes of oscillation. Figures **c** and **f** give the FFT amplitude spectra for 4-bit pattern 1111 for = 1.5 ns & 3.6 ns respectively. Figure **g** (**j**) shows the 4-bit binary input pulse with input parameters I0 = 0, I1 = 3.5 mA, ∆t = 4 ns and = 1.5 ns (3.6ns), for the 4-bit pattern 0101. For both = 1.5 ns (Fig. **h**) and = 3.6 ns (Fig. **k**), the Mx amplitudes corresponding to both the bit 1 pulses are the same. Figures **i** and **l** give the FFT amplitude spectra for 4-bit pattern 1111 for = 1.5 ns & 3.6 ns respectively. Similar to Supporting information section S3, this prevents the separation of any cyclic permutations of 4-bit patterns for both = 1.5 ns and = 3.6 ns.

**Supplementary material 4: Magnetization dynamics of 16 combinations of 4-bit digit pattern separation on modified pulse scheme with Ie = 3.0 mA, δ = 5 ns, I0 = 1.2 mA, I1 = 2.4 mA, ∆t = 4 ns, = 3.0 ns.**

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**Figure. S4.** Figure **a** shows the magnetization dynamics corresponding to the 16 different 4-bit input patterns for the modified pulse scheme with input parameters Ie = 3.0 mA, δ = 5 ns, I0 = 1.2 mA, I1 = 2.4 mA, ∆t = 4 ns, = 3.0 ns. Figure **b** gives the FFT amplitude spectra corresponding to the 16 different 4-bit input patterns. Note that the FFTs are calculated using Mxin the range of the input patterns as shown in the 0000 bit pattern.

**Supplementary material 5: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with Ie =1.4 mA, δ =5 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns.**

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**Figure S5.** Figures **a**, **b** and **c** show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 0001 with input parameters Ie =1.4 mA, δ =5 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns. Similarly, Figs. **d** (**g**), **e** (**h**) and **f** (**i**) show the 4-bit binary input, pulse corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 0010 (1111) with the same input parameters. Note the difference betweeen the FFT amplitude values filtered at 9.0 GHz. The low value of separability index (SI) reported for Ie =1.4 mA can be directly correlated with filtered FFT amplitude values in close rangefor the different 4-bit input patterns.

**Supplementary material 6: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with Ie =5.0 mA, δ =5 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns.**

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**Figure. S6.** Figures **a**(**d**), **b**(**e**) and **c**(**f**) show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 0001 (0010) with input parameters Ie =5.0 mA, δ =5 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns. Similarly, Figures **g**(**j**), **h**(**k**) and **i**(**l**) show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 1110(1111) with the same input parameters. Note the difference betweeen the FFT amplitude values filtered at 9.0 GHz. The high value of separability index(SI) reported for Ie =5.0 mA can be directly correlated with the filtered FFT amplitude values for the different 4-bit input patterns. However, the SI for Ie =5.0 mA is lower than that of Ie =3.0 mA because, as seen in Figs. **h** & **k**, for Ie =5.0 mA, the precessions excited by the excitatory pulse are already in the auto-oscillation mode, leading to saturated Mxamplitudes for all subsequent input bit 1 pulses. This leads to the filtered FFT amplitude values being much closer for Ie =5.0 mA, causing slightly lower SI as compared to Ie =3.0 mA.

**Supplementary material 7: Investigation of magnetization dynamics and 4-bit digit pattern separation on modified pulse scheme with Ie =5.0 mA, δ =1, 20 & 25 ns, I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns.**

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**Figure. S7.** Figures **a**(**d,g**), **b**(**e,h**) and **c**(**f,i**) show the 4-bit binary input pulse, corresponding magnetization dynamics and FFT amplitude spectra respectively for the 4-bit pattern 1010 with input parameters Ie =5.0 mA, δ = 1 ns (20 ns, 25 ns), I0 =1.2 mA, I1 =2.4 mA, ∆t =4 ns, =3ns. The effect of the excitatory pulse on the input binary pattern decreases with increasing δ. This leads to decreasing Mxamplitudes and therefore decreasing the filtered FFT amplitudes at 9.0 GHzwith increasing δ. Moreover, the reduced filtered FFT amplitudes for all 16 combinations of 4-bit input patterns causes the SI to decrease with increasing δ.