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Spin Hall Nano-Oscillator Arrays: Towards GHz Neuromorphics

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Abstract

This thesis explores the vibrant phenomena of spin Hall nano–oscillators (SHNOs); from wideband oscillation at the GHz range, through propagating spin–wave emission, to mutual synchronization in two–dimensional SHNO arrays, and tries to lay the foundation for a far-reaching SHNO technology, targeting magnonics, microwave signal generation, and neuromorphic computing.

After a short introduction to the theoretical background in Chapter 1, in Chapter 2, ways of improving the spin transport properties between NiFe and Pt are explored: an 0.4 nm ultra–thin layer of Hf at the NiFe/Pt interface is found to reduce the threshold current by 20% as a result of the change in spin mixing conductance $G_{\mathrm{eff}}^{\uparrow\downarrow}$. Then, W/CoFeB/MgO stacks with perpendicular magnetic anisotropy (PMA) are used to demonstrate wide frequency tunability and sub–mA threshold currents in CMOS compatible SHNOs. By further increasing the PMA, the auto–oscillation frequency exceeds the ferromagnetic resonance (FMR) frequency, turning the SHNO into a propagating spin–wave emitter in which the propagation wave–vector is tunable with applied current and field. Finally, a GHz nano-scale SHNO modulated by an 80 MHz radio–frequency (RF) current is presented. The modulation needs no bulky microwave mixer, promising a compact modulator unit.

Chapter 3 introduces two–dimensional SHNO arrays. Robust mutual synchronization is demonstrated in arrays accommodating up to 64 oscillators, achieving record high quality factors of 170,000 at an operating frequency of 10 GHz. Injection of two external microwave signals reproduces the two-dimensional synchronization maps used in neuromorphic vowel recognition.

Chapter 4 emphasizes the importance of individual SHNO control in arrays. Gated SHNOs are demonstrated with substantial voltage tuning of the threshold current and the SHNO frequency. Voltage controlled mutual synchronization is also demonstrated. The $MgO/AlO_x/Si_3N_4$ gate is found to exhibit a memristive behavior governed by ion migration and acts as an embedded memory making each SHNO a complete non-volatile oscillator with integrated weights. The exciting nature of coupled non-volatile oscillator arrays controlled by electric field could lead to a paradigm shift in non–conventional computing.

Chapter 5 discusses the implications of the demonstrated SHNO technology and how it may impact future applications.

Keywords: spin Hall effect, spin Hall nano-oscillators, microwave, spin wave, synchronization, neuromorphic computing, memristor.