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Towards two-dimensional magnon spin transport in ultrathin magnetic insulator films

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Chapter 1

Introduction

1.1 Moore's law: Rise and crisis

More than 3.7 billion years after its birth, life from the earth walked on the moon for the first time on July 20th, 1969. One of the greatest achievements behind Armstrong's small step is the Apollo Guidance Computer, which is one of the first computers based on integrated circuits with about 10000 transistors in 1952 cm^2. About fifty years later, in the autumn of 2021, Apple Inc. announced their new chip, M1 Max, with 57 billion transistors in 432 mm^2. The transistor density increases from 0.05 $\mathrm{Tr/mm}^2$ to 1.32 billion $\mathrm{Tr/mm}^2$. This fantastic improvement in the semiconductor industry was predicted or summarized by Moore that the transistor density in microchips doubled every two years.

The first transistor was invented by Brattain and Bardeen at Bell Labs in 1947, and it is a point-contact structure measured 1.27 cm in height. A single transistor has miraculously shrunk to nanometers over the last decades, which benefits from the evolution of its configuration. Nowadays, competition between Taiwan Semiconductor and Samsung Electronics, the two main chip manufacturers on our planet, has accelerated the semiconductor industry into 5 nm processes. The design of those most advanced chiplets is mainly based on a 3D configuration, Fin field-effect transistor (FinFET), where the prototype was reported by Hisamoto *et al.*[1] in 1998.

However, the legend of Moore's law could be out of date one day. Even before Moore published his prestigious prediction, people had realized that the trend of miniaturization of electronic devices was unavoidably limited by the physical nature of the world[2–4]. According to a prospect from Keyes in 1988[5], a bit would be able to be stored and manipulated by an atom around 2020 (shown in Fig. 1.1). In fact, the flash chip with the highest storage densities now, Penta-level cell NAND flash memory, stores a bit at micrometer size, which was introduced by Solidigm in mid-2022.

Information density is not the only formidable challenge that we face today, and the enormous energy consumption from modern electronics is incredibly huge. It cost 205 TWh just to keep the data centers around the world running in 2018[6] (1 TWh= 10^9 kWh), and in the same year, the energy use per person in the Netherlands is 57,062 kWh[7]. The Joule heating from electronic devices also hinders the miniaturization of traditional electronics. A working device constantly sheds heat, and its central processing unit (CPU) can easily overheat. The heating problem thermally throttles the CPUs and also consumes vast amounts of electricity. Facebook built its first European data center in Luleå, a Swedish city close to the Arctic Circle, so they can utilize the climate of the city to cool down the servers. Meanwhile, Microsoft

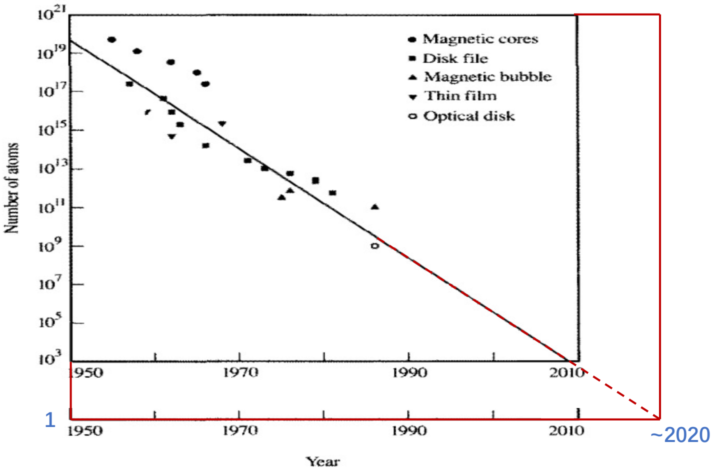

Figure 1.1: *The number of atoms used to store a bit as discrete magnetic entities in file technologies (extended from [5]).*

started to deploy its data center in the Pacific Ocean for cooling.

Moore's law is the cornerstone of the modern information society, whereas the traditional microelectronics industry is approaching its limits. *There is plenty of room at the bottom*, as Feynman said in 1959. Innovations from the fundamental side are necessary to meet the increasing demands of society, and many beyond-Moore technical routes have developed competitive prototypes for next-generation information devices. In this thesis, we focus on one of those promising technologies, spintronics, which is based on the spin angular momentum instead of the electric charge to extend Moore's law.

1.2 Spintronics: For the post-Moore's law era

Spin is the intrinsic angular momentum of particles. The postulate of electron spin was inspired by the puzzle of the anomalous Zeeman effect[8]. Uhlenbeck and Goudsmit, two young students in Leiden, explained their hypothesis of the spinning electron to interpret the anomalous Zeeman effect in 1925 and 1926[9, 10]. Although Pauli formulated the exclusion principle at the end of 1924[11], he adamantly rejected this idea until 1926. After converting his opinion, he developed the Pauli spin matrices[12]. At present, people have been familiar with the concept that the electron carries spin angular momentum, and it has two quantized states, spin up and spin down.

The technology revolution is boosted by utilizing electron spin to develop next-generation microelectronics devices with high speed, low energy consumption, and high information density. Such promising prospects gave birth to a new research field, spin electronics, or spintronics. The discovery of giant magnetoresistance (GMR) in 1988 is the beginning of spintronics[13, 14]. Fert and Grünberg were later awarded the Nobel Prize in Physics.

Over the last 35 years, spintronics is advancing with unprecedented speed. Spin-transfer torque[15, 16], spin-orbit torque[17], spin Hall effect[18], Rashba-Edelstein effect[19], and many other fundamental phenomena have been observed and studied. These developments have great potential in magnetic memories, magnetic sensors, radio-frequency and microwave devices, and logic and non-Boolean devices, which could deeply impact the information technology soon[20].

1.3 Magnonics: Waltzing spins in magnetic insulators

A magnon, or spin wave, is the collective excitation of electron spins in magnets. This concept was introduced by Bloch to explain the temperature-dependent spontaneous magnetization of ferromagnets in 1930[21]. Different from electrons, a magnon is a chargeless quasi-particle that can be transported in magnetic insulators without the heating effect. Due to this unique property, magnon spintronics, also called magnonics, has attracted a lot of attention for its potential application in microelectronics. The study of magnonics focuses on the excitation, propagation, manipulation, and detection of magnons. A detailed theoretical description of magnons and related phenomena is given in Chapter 2. We explore new frontiers for magnon transport in this thesis, where the magnon transport is approaching to two-dimensional transport limit at room temperature.

1.4 Motivation and outlines

This thesis studies magnon-related phenomena in ultrathin ($\sim$10 nm) yttrium iron garnet films. The effects investigated and the methods developed in this thesis enrich the toolbox to design ultra-compact spintronics devices. This thesis is built up by the following chapters, of which a brief overview is given below:

- *Chapter 2* includes the basic physics to understand the effects studied in this thesis.
- *Chapter 3* introduces the fabrication process and the electrical measurement methods applied in this thesis.
- *Chapter 4* presents the discovery of a counter-intuitive giant magnon spin conductivity reaching 1.6×10^8 S/m in record-thin magnetic insulating films of YIG, which is 3-4 orders higher than that of bulk YIG. It is related to a transition from three-dimensional (3D) to two-dimensional (2D) magnon transport when the film thickness approaches a few lattice constants.
- *Chapter 5* uses a three-terminal magnon transistor configuration to study the non-linear phenomena in ultrathin YIG films. The modulation efficiency of magnon transport in magnon transistors is greater than 200% in such thin films. However, the gate-width-dependent experiments indicate the physics of non-linear magnon transport is complicated.

- *Chapter 6* demonstrates that the YIG maintains robust magnetic properties in unit-cell thin films, and the nanogranular unit-cell thin YIG films have strong perpendicular magnetic anisotropy.
- *Chapter 7* investigates the role of spin-related torques in non-linear magnon transport with a cross structure of Pt on YIG.

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