Fabrication and Characterization of Nanocontact Spin-Torque Oscillators

SOHRAB REDJAI SANI

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Abstract

The manufacturing of nanocontact-based spin-torque oscillators (NC-STOs) has opened the door for spintronic devices to play a part as active microwave elements. The NC-STO has the capability of converting a direct current into a microwave signal, and vice versa, by utilizing the spin transfer torque (STT) in ferromagnetic multilayer systems. However, the high-frequency operation of NC-STOs typically requires high magnetic fields and the microwave power they generate is rather limited. As a result, NC-STOs are not yet commercially used, and they require improvements in both material systems and device geometries before they can find actual use in microwave applications.

In order to improve and advance this technology, NC-STOs are required with both different nanocontact (NC) sizes and geometries, and using different stacks of magnetic materials. This dissertation presents experimental investigations into the manufacturing of such devices using different fabrication techniques and a number of different magnetic material stacks. Currently, the fabrication of NC-STOs is limited to advanced laboratories, because NC fabrication requires high-resolution lithography tools. In the present work, we have developed an alternative method of fabrication, which does not require such tools and has the capability of fabricating NC-STOs having one to hundreds of NCs in a variety of sizes, possibly down to 20 nm. Devices fabricated with this method have shown mutual synchronization of three parallel-connected NCs, and pairwise synchronization in devices with four and five NCs.

Furthermore, the present work demonstrates low-field operation (down to 0.02 Tesla) of NC-STOs at a record high frequency of 12 GHz. This was achieved by implementing multilayers with a perpendicular magnetic anisotropy (PMA) material in the free layer of the NC-STO. In addition, the fabricated devices revealed an unexpected dynamic regime under large external applied field (above 0.4 Tesla). The new dynamic regime was found to be due to an entirely novel nanomagnetic dynamic object â a so-called magnetic droplet soliton, predicted theoretically in 1977 but not experimentally observed until now. Detailed experiments and micromagnetic simulations show that the droplet has very rich dynamics.

Finally, spin-torque-induced transverse spin wave instabilities have been studied. A NC-STO with a material stack consisting of a single ferromagnetic metal sandwiched between two non-ferromagnetic metals was fabricated. Prior to this work, evidence of spin wave instabilities was reported as resistance switching in nanopillar- and mechanical point contact based STOs. In the present work, the fabricated NC-STOs showed actual microwave signals up to 3 GHz under zero applied field with strong current hysteresis. All the fabricated NC-STOs open up new means of studying STT in different environments, in order to resolve their current drawbacks for industrial applications.

Keywords: Spin-torque oscillators, phase locking, spin wave, giant magnetoresistance, spin transfer torque, thin films.
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List of symbols

$\mu_0$  Vacuum permeability

$f$  Frequency

$Ar$  Argon

$Al$  Aluminum

$AP$  Anti-Parallel

$An$  Anti-Vortex

$Au$  Gold

$FL$  Brillouin-Light-Scattering

$BC$  Bottomcontact

$CIP$  Current-In-Plane

$CPP$  Current-Perpendicular-to-Plane

$f$  Frequency

$FMR$  Ferromagnetic-Resonance

$FL$  Gigahertz

$FL$  Giant-Magnetoresistance

$FL$  External Field

$H$  Anisotropic-Strength

$H_{droplet}$  Droplet-Field

$I_{droplet}$  Droplet-Current

$MHz$  Megahertz

$ML$  Multilayers

$MRAM$  Magnetic-Random-Access-Memory
<table>
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<tr>
<th>Symbol</th>
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<tr>
<td>$M_s$</td>
<td>Saturation-Magnetization</td>
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<tr>
<td>MTJ</td>
<td>Magnetic-Tunneling-Junction</td>
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<td>NC</td>
<td>Nanocontact</td>
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<tr>
<td>Oe</td>
<td>Oersted</td>
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<tr>
<td>OOP</td>
<td>Out-of-plane</td>
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<tr>
<td>Oe</td>
<td>Oersted</td>
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<tr>
<td>Ortho</td>
<td>Orthogonal</td>
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<td>P</td>
<td>Parallel</td>
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<td>PMA</td>
<td>Perpendicular-Magnetic-Anisotropy</td>
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<td>PSV</td>
<td>Pseudo-Spin-Valve</td>
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<tr>
<td>RF</td>
<td>Radio-Frequency</td>
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<td>SHE</td>
<td>Spin-Hall-Effect</td>
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<tr>
<td>STO</td>
<td>Spin-Torque-Oscillator</td>
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<tr>
<td>STT</td>
<td>Spin-Transfer-Torque</td>
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<td>SV</td>
<td>Spin-Valve</td>
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Publication List

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Summary of included papers

Paper I:
This article presented the initial stages of the fabrication and characterization of spin transfer torque (STT) devices. Studying STT requires current densities on the order of $10^8$ A/cm$^2$, which can be achieved by implementing a nanosized path for the current. In this work, a new fabrication sequence combining “optical” and “hole-colloidal” lithography was introduced to make nanosized openings. Finally, the fabricated devices were measured; they showed reliable electrical properties.

Contributions: Design and fabrication of the devices. Performed electrical characterizations. Contributed to writing the manuscript.

Paper II:
This paper demonstrated spin transfer torque (STT) switching in multi-nanocontact STT devices fabricated using hole-mask colloidal lithography. We also studied STT device resistance and switching properties, as a function of applied magnetic field and nanocontact current. At low nanocontact currents, magnetoresistance measurements showed sharp single-step switching in low switching fields. When the current was increased, the switching became multistep, and the switching field increased dramatically. We explained these results as arising from a transition from a predominantly single-domain-like switching to switching involving a vortex state. Micromagnetic simulations corroborated this picture, indicating that a single magnetic vortex nucleates in between the nanocontacts through the influence of the total Oersted field generated by the nanocontact ensemble.

Contributions: Material deposition, device fabrication, and all characterizations performed with SEM and transport characterization. Data analysis. Contributed to writing the manuscript.

Paper III:
In this work, we presented a technique that opens up the possibilities of fabricating a variety of STT devices, specifically STO arrays, without expensive high-performance lithography equipment. By utilizing small polystyrene spheres, multinanocontact
STOs were fabricated. The structures could be organized in patterns or randomly distributed on the surface with tunable densities and sizes. Being able to control the density, or spacing, of the contacts is crucial for synchronized STO arrays. Using this technique, we fabricated nanocontact STO devices with a controllable number and size of nanocontacts on a Co-Cu-NiFe giant magnetoresistance (GMR) thin-film stack. A statistical analysis of the number of nanocontacts for 100 nm and 80 nm diameters was presented. Frequency-generation from a single device with a single nanocontact, and coherent synchronization from devices with two and three nanocontact, have been observed. Devices with four or five nanocontacts showed partial synchronization.

Contributions: Material deposition, device fabrication, and characterizations of all SEM and RF measurements. Data analysis. Contributed to writing the manuscript.

Paper IV:
A nanocontact-based STO was fabricated, with a material stack consisting of Co as the fixed layer (in-plane magnetization) separated by Cu from a [Co/Ni] multilayer (orthogonal magnetization) free layer. We have experimentally reconfirmed that the frequency generated has $\mu_0(H_k-M_s)$ dependency. As a result, the fabricated device showed 12 GHz signaling under a 0.02 T field, which is considered to be a very small field for such devices. This makes it possible to achieve even higher frequencies with greater material optimization.

Contributions: Device fabrication and initial transport characterization. SEM investigation of devices. Contributed to data analysis and the writing of the manuscript.

Paper V:
This article demonstrated an environment capable of sustaining dissipative solitons with their rich dynamics. The system investigated was an NC-STO consisting of a fixed layer with in-plain magnetic anisotropy and a free layer with perpendicular magnetic anisotropy. Micromagnetic simulation carried out on these devices confirmed the presence of droplet dynamics in these systems, and suggested a wide range of automodulation frequencies, such as spinning and breather droplet modes. Finally, field and the current tunability of the droplet were investigated.

Contributions: Device fabrication, initial transport characterization and SEM investigation of devices. Contributed to data analysis and the writing of the manuscript.

Paper VI:
We demonstrated spin transfer torque (STT) driven microwave signal generation, from about 250 MHz to above 3 GHz, in single permalloy layers under a nanocontact
with a diameter of 100 nm. The threshold current for signal generation was found to be strongly hysteric. The microwave signal showed a number of harmonics. Zero-field operation was straightforward, and the microwave frequency increased quasilinearly with drive current. All these observations are consistent with STT-driven motion of a vortex-antivortex pair nucleated by the Oersted field under the nanocontact. While the generated power was about 10 dB smaller than the best GMR-based nanocontact spin-torque oscillators, the linewidth of 6 to 100 MHz is of the same order.

**Contributions:** Material deposition, device fabrication, and all characterization done with SEM and transport measurement. Contributed to the writing of the manuscript.
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During the time I was working on my PhD thesis I had the pleasure of working with many inspiring individuals that formed a productive environment for me to work in. I would like to thank all the people who contributed in forming such stimulating atmosphere that helped me over the years to complete my projects successfully.

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Chapter 1

Introduction

Spintronics is a research field that takes into account the spin of the electrons and associates it with the electronic-charge properties of solid-state matter and the magnetic moment. It has already given rise to a new generation of devices [1]. The origin of spintronics was in 1988, when Albert Fert and Peter Grünberg separately discovered giant magnetoresistance (GMR) [2,3] in ferromagnetic (FM)-nonmagnetic (NM) metallic multilayers. For this discovery, Fert and Grünberg jointly won the 2007 Nobel Prize [4,5] in Physics. The discovery resulted in many advances in nanomagnetism and spintronics [1], and has also defined the pathway to data storage with GMR-based read-heads and Magnetic Random Access Memories (MRAMs) [6–8]. One of the most important aspects of their discovery is that the electrical current in these structures becomes spin-polarized. Over the past couple of decades, this effect, in combination with other new phenomena, has opened up many other applications, including spin-torque oscillators (STOs).

Slonczewski [9] and Berger [10] predicted in 1996 that, when a sufficiently high current density (i.e., $10^8$ A/cm$^2$) passes through magnetic multilayers (ML), it should produce a direct effect on the magnetic state. In a trilayer FM/NM/FM structure, when the current passes through the first magnetic layer, it becomes spin-polarized and thus carries angular momentum. The current polarization remains unchanged after passing through the nonmagnetic layer, when it hits the interface of the second FM. In this way, the spin-polarized current can apply a spin transfer torque (STT) on the adjacent magnetic layer, and when the current is sufficiently large, it causes switching or reversal of the magnetization. An application of these phenomena is to convert a direct current (DC) into an alternating current (AC) voltage, and the result of this is that the fabrication of DC-controlled microwave generators becomes possible [11]. The generated signal can be explained as time varying magnetoresistance (MR) in the STO active device attributed to giant magnetoresistance (GMR) [12] or, tunneling magnetoresistance (TMR) [13]. Consequently as the free-layer magnetization rotates with respect to the static magnetization of the fixed layer, the speed of the precession is associated with the fre-
CHAPTER 1. INTRODUCTION

quency generated. The first DC-driven microwave generator resulting from STT was reported by Tsoi et al. \[14\] with a nanopoint contact geometry. Later on, different geometries were fabricated, including nanopillars \[15,16\], lithographically defined nanocontacts \[17\], electrochemically grown nanowires \[18,19\], manganate junctions \[20\], and tunneling-junction nanopillar structures \[21\]. All of these are classified as STOs with very small footprints (<100nm) \[22\]. They are active microwave devices with interesting properties, including large frequency tuning ranges based on applied current and external field \[17,23\], high modulation rates \[24–26\], and compatibility with silicon technology (such as MRAM) \[6,7\]. STOs also provide an ideal platform for studying spin dynamics in different size scales from a few nanometers up to micrometers, as well as different phenomena such as the spin Hall effect (SHE) \[27–29\], the Rashba effect \[30\], domain wall motion \[31\], thermal effects \[32\], optical effects \[33\], and mechanical effects \[34\]. One other very interesting aspect of Nano-Contact Spin Torque Oscillators (NC-STOs) is that these devices are suitable environments for studying magnonics \[35,36\]—that is, the electronics of Spin Waves (SW). This results from the fact that they can easily and reliably convert an electrical current to magnetization oscillation in the GHz range.

A microwave signal generator as small as an STO and possessing a tunable frequency range with parameters (such as current or voltage) capable of producing sufficient power without the need for an external magnetic field is highly demanded in the communications industry. However, apart from the fact that the frequency generated in STOs can be controlled easily with DC current, they can only generate high frequencies under large applied fields. For example, in the case of in-plane GMR stack-based NC-STOs, external magnetic fields of 1 T are needed to generate a signal in the 20 GHz range \[23,37\]. Under zero external applied field, these devices instead generate frequencies below 500 MHz that are associated with gyrotropic vortex motion \[38\]. This vortex dynamic can generate much higher microwave power, but lacks the wide current tunability. Thus, this technology still needs improvements if it is to become applicable in the industry. Both theoretical works and experimental results show that a current and microwave shunt on one hand, and electrical mismatch with the RF load on the other, both contribute to the low power in NC-STOs \[39\]. This suggests the need to engineer a new device to solve these problems \[39\]. At the same time, the only STOs that display sufficiently promising output power are TMR-based STOs, but these lack high-frequency operation and also have low quality factors \[40,41\]. However, there are other potential applications for STOs apart from signal generators, such as microwave detectors \[42\], diodes \[43\], and magnetic sensors \[44\]. It is thus necessary to develop, study, and optimize STOs with new geometries and materials.

The present challenges in STOs can be described as follows: i) low power, ii) the large external field required for device operation, iii) the complexity of the material stack, and iv) the difficulties of nanofabrication. In the following paragraphs, we present new techniques that may help to improve NC-STOs, in particular with regard to these challenges.
One of the difficulties with the STO fabrication is the requirement for advanced nanolithography systems, such as Electron-Beam Lithography (EBL), UV lithography, or nanoimprinting. In the present work, we have developed a new fabrication method that does not rely on advanced lithography tools to make nanosize openings as small as 20 nm. This method involves hole-colloidal lithography (HCL) and optical lithography, and is capable of making a wide range of NC geometries, from one NC up to hundreds of NCs per device. The fabrication of multiple-NC STOs is a way of solving the low power problem in STOs. Since STOs generate spin waves that synchronize over a shared medium, this will result in power increases, as reported in 2005 in double NC systems. But until now, no experimental evidence of further synchronization has been reported, possibly due to the fact that the fabrication process is complicated.

As mentioned, one of the present issues in STO technology is the external field requirement for operation at frequencies above 500 MHz. In order to achieve higher frequency operation under zero or a very small external field, a material stack with an in-plane (IP) fixed layer and an out-of-plane (OOP) free layer is studied. In the present work, the implementation of this material stack into an NC-STO is experimentally demonstrated. The IP fixed layer can be easily fabricated with high spin-polarized materials, such as Co or CoFe, and the OOP free layer can be manufactured using [Co/Ni] multilayers with tunable magnetization (M_s) and perpendicular magnetic anisotropy (PMA). As a result, the fabricated devices can generate frequencies of up to 12 GHz under external fields as low as 0.02 T.

The devices fabricated with a Co fixed layer and a [Co/Ni] multilayer with strong PMA free layer also made it possible to investigate magnetic droplets, as was predicted from recently developed theories. This nanomagnetic and magnetodynamic object was first brought up by Ivanov and Kosevich, in 1977. They showed that if the damping in a two-dimensional system with PMA can be ignored, then the Landau-Lifshitz equation would allow for a family of conservative magnetic solitons called magnon drops. Over the past 35 years, many theoretical studies have dealt with the possibility of such dynamics, but so far there has been no experimental confirmation. The concept of a dissipative magnetic droplet was introduced by Mark Hoefer in 2010, and be viewed as a magnon drop in a dissipative medium driven far from equilibrium. These characteristics make NC-STOs with high PMA free layers and IP fixed layers strong candidates for studying dissipative solitons. These are also known to display remarkable dynamics, such as periodic breathing and automodulation.

To simplify the material stack, reduce roughness, and to eliminate coupling between the fixed and free layers, it is possible to explore the current-induced spin wave excitation in NC-STO with material stack consist of a single ferromagnetic (FM). Early experiments on nanopillar and point contact geometries fabri-
cated with single FM layers have shown that an unpolarized current applied on a FM layer can generate enough STT to cause instability \cite{54,55}. Theory predicts that spin filtering by the single FM creates a spin accumulation at both it's NM interfaces \cite{53,56,57}. If the two interfaces are symmetric, then the net torque will be zero. However, any asymmetry between the two interfaces will generate a net STT on the FM layer, which can be substantial. As in the case of conventional GMR-based NC-STO devices, only one current polarity will lead to negative damping. Here we present a study of the fabrication of NC-STOs with permalloy as the FM layer sandwiched between Cu electrodes. These devices can generate up to 3 GHz frequency under zero applied field, with linewidths as low as 6 MHz being recorded.

**Thesis outline**

In chapter 2, the fabrication and characterization tools used in the present work are briefly introduced. Chapter 3 presents a summary of fabrication process for making NC-STOs. Chapter 4 gives a brief summary of devices fabricated with the HCL method. Devices with a single 100-nm or 80-nm NC were successfully fabricated, and in devices with 3 NCs, mutual synchronization was observed. Also, pairwise synchronization in devices with 4 and 5 NCs was recorded. In chapter 5, a summary of results extracted from NC-STOs with a PMA free layer and an in-plane fixed layer is given. These devices demonstrate high-frequency operation in low applied field and also present interesting droplet dynamics. Chapter 6 summarizes the results from the single-layer NC-STOs. The fabricated devices demonstrated the generated RF signal, under zero and in-plane external magnetic field. In chapter 7, the present work is summarized, and the outlook for future work based on the present findings is outlined.
Part I

Fabrication and Characterization Methods
Chapter 2

Method and techniques

The fabrication of electronic devices, including NC-STOs, requires the utilization of a variety of tools. One of the most important parts of NC-STO fabrication is the formation of the active area, which in these devices is the metallic multilayer. Deposition of multilayer is commonly carried out using magnetron sputtering. Afterwards, the boundary of the devices must be defined. This requires lithography and etching steps, followed by the deposition of insulator layers to protect the active area. This step is crucial, since the electrical path will be defined by this layer. The formation of the electrical path is the final step in the fabrication of NC-STOs. In the following chapter, the tools used for fabrication of these devices are explained briefly.

In order to fabricate devices with high yield, it is necessary to monitor the processing closely. In the present work, most of the characterization techniques evaluating were to evaluate metallic thin film properties (e.g., GMR) before and during processing. Finally, microwave characterization of the fabricated NC-STOs was performed with a custom-built setup. In the following chapter, these characterization methods are briefly explained.

2.1 Physical vapor deposition

The NC-STO process flow contains a variety of layers above the silicon/silicon-oxide substrate. These include thin metallic layers. Physical vapor deposition (PVD) is a technique for depositing thin films with almost no chemical reaction using a solid source “target”. Since this technique does not rely on any chemical reaction and uses only physical methods, it can deposit almost any material onto a vast variety of substrates. In the following chapter, the two methods most commonly used in the present work are introduced.
CHAPTER 2. METHOD AND TECHNIQUES

Electron-beam evaporation

In an electron-beam evaporation system, an electron-beam source heats the solid source targets to their melting points. The chamber is designed in such a way that the evaporating materials can travel and reach the substrate to form a thin film. In the work for this thesis, a Provac PAK 600 Coating System was used. This system can monitor the deposited material thickness with a resolution of 0.01(Å), based on the atomic weight. It thus has the capability of depositing different materials in a wide range of thicknesses. For example, to test different top contact metalization for STOs, gold, silver, and aluminum were deposited with thickness from 100 nm to 2 µm. It is also possible to deposit material with thicknesses of a few nanometers.

Sputter deposition

Sputtering deposition is a commonly used technique for the manufacturing of multilayer magnetic materials. In this method, the materials are sputtered away from the target by means of high-energy ions while the target temperature remains low. The targets are thus not damaged by the high temperature, and deposition of material with more than one element, such as permalloy, is possible. Also, to prevent any changes in the property of the target, the dislodging process is carried out with high-energy inert gas ions (such as argon) \[58\].

In the present work, an AJA ATC Orion-8 with seven guns is used. This system is a confocal sputtering system, with the multi magnetron sputtering sources placed a specific coordination in a circular pattern and they are directed towards a common focal point. As shown in Fig. 2.1 when the substrate is placed in proximity to the focal point and rotated on its own axis it is possible to deposited highly uniform single and multi-layers (co-sputtering) films. In this system, the targets are two inches in diameter and layers with a uniformity of ±2% can be deposited on a

Figure 2.1: Schematic of confocal sputtering system with rotational substrate.
4-inch substrate [59]. Also, the present configuration geometry has the capability of depositing more than one target simultaneously, by using multi sputtering guns. Depending on the depositing material, it is possible to use RF or DC power supplies for the sputtering guns to generated plasma. For depositing conductive material such as aluminum of gold it is possible to utilize either RF or DC power supply but for nonconductive materials such as MgO or SiO$_2$ it is required to use RF power supply. Furthermore, by stopping the substrate rotation, it is possible to fabricate samples with gradient thicknesses. This is used to study materials with a broad range of thicknesses while eliminating sample to sample manufacturing variation.

The deposition rate is an important parameter which determines the quality of the fabricated multilayers. Therefore, it is crucial that it be calibrated before manufacturing begins. In the present study, the deposition parameters, such as power, base pressure, and working pressure are well studied and calibrated before fabrication of the material stack. In this way, we have tried to make multilayers with as little roughness as possible, since it can degrade the spin-valve quality to a large degree.

2.2 Plasma-enhanced chemical vapor deposition (PECVD)

In STO technology, forming a high-quality silicon dioxide layer is crucial to device performance. At the same time, there are restrictions on the temperature that GMR multilayers can sustain without suffering degradation of their magnetic properties. This occurs at around 200°C [60]. However, the processing temperature for forming a high-quality, nonporous silicon dioxide layer is much higher than 200°C. In order to solve this problem, the plasma-enhanced chemical vapor deposition (PEVD) method is used. In this method, the plasma source and heat source provide the energy needed for the chemical reaction between the gasses (SiH$_4$ and N$_2$O), as shown in equation (2.1) [61], to form a silicon dioxide film of adequate quality.

\[
\text{SiH}_4(\text{gas}) + 2\text{N}_2(\text{gas}) \rightarrow \text{SiO}_2(\text{solid}) + 2\text{H}_2 + 2\text{N}_2(\text{gas})
\] (2.1)

In the present study a Plasmalab 80 Plus Oxford PECVD System is used to form the silicon oxide layer. The layer separates the material stack in the active area from the top electrodes in STO device. Moreover, the STO’s current path is formed in this layer. In conclusion, the layer is a crucial part of the fabrication that defines the device’s functionalities and limitations.
2.3 Etching

In the fabrication of electronic devices, the formation and separation of distinct elements is usually done by etching steps. In the present work, two etching techniques were employed. First, pure argon sputter etching was used to define the device boundary and to form its active area. Second, fluorine-based reactive ion etching (IRE) steps were implemented to produce openings in the insulation layer. In the following two sections, these etching processes are introduced.

Magnetic material etching

Metallic multilayer structures are known to be more sensitive to temperature than semiconductor materials. Additionally, metallic structures begin diffusing into one another at temperatures of around 200°C. So through the course of device fabrication, it is hence crucial to monitor the temperature closely. In the etching of magnetic materials, the ion-milling method has mostly been used. In the present work, we have utilized a RIE chamber in an applied Materials 5000 Mark II system. Despite the recommendation to use Cl₂-assisted RIE, we have found that pure Ar plasma etches the multilayer stack more homogeneously. Since this system has a helium cooling system on the wafer back side, the temperature does not increase to a level sufficient to degrade the material stack properties during the etching. This was tested on a wafer with a spin-valve stack, and neither the shape nor the value of the GMR peaks were changed by the etching step. Also thanks to the cooling system, the photoresists used in the processing step are not so crosslinked that removing them becomes impossible after etching.

Reactive ion etching (RIE)

Selectively removing material without affecting the rest of the sample is necessary to fabricate high-performance devices. At the same time, the etch profile and pattern shape are also very important in fabricating devices with similar properties. By using RIE, these requirements are achieved to a high degree. Since this method targets a specific chemical reaction and uses low power, physical plasma etching can remove the by-product. In the present work, we have used an Oxford Plasma System (the Plasmalab 80 Plus) to etch the SiO₂ insulation layer. The etching recipe employed here uses Ar and CHF₃ gasses. The fluorine in the CHF₃ reacts with Si (this is the chemical reaction side), and the Ar ions in the plasma removes the by-product, which is the physical part of the process. The etching recipe is modified in such a way to make it possible to produce a nanosized opening into the SiO₂ layer with both photoresists (1.2 µm thick) and EBL resists (120 µm thick), while at the same time not affecting the material stack. Similar etching tests, explained in the previous section, confirmed that the material stack was not affected by the present
2.4 Lithography

The fabrication of electronic devices requires multiple lithographical steps to define different components. Since NC-STOs have both micron-sized and nanosized features, multilithography systems are used in the manufacturing process according to the required resolutions of each step. In this work, five lithography steps were used to fabricate high-quality NC-STOs. Depending on the size of the feature targeted, two systems were utilized. For resolutions not higher than 650 nm, an XLS 7500/2145 i-line stepper was employed; for manufacturing nanosized features, an electron-beam lithography (EBL) system was used. The XLS system is a 100 mm wafer-based stepper system with auto alignment capability. The resolution of this system is limited to 650 nm, but with help from double exposure technique and oxygen plasma ashing, openings as small as 450 nm were manufactured. This system was also used in combination with the hole-colloidal lithography method to make nanosized openings. The EBL system was mostly used for fabrication of opening below 100 nm in size. Based on the processing step, different resist were used, such as 712 positive resists, lift-off resists (LOR), ZEP resists, PMMA (EBL) resists, and AZ nLOF 2035 negative resists.

2.5 Giant magnetoresistance (GMR) measurements

Magnetoresistance (MR) is defined as the change in electrical resistance due to magnetic field. The so-called giant magnetoresistance (GMR) refers to the magnetoresistance found in magnetic multilayers, as discovered by the Physics Nobel Prize winners of 2007, Albert Fert and Peter Grünberg \cite{2,3}. This effect can be defined as the change in the electrical resistance of the magnetic multilayers due to a change of angle between the magnetization of adjacent magnetic layers. The resistance changes from low to high when the magnetization goes from parallel (P) to antiparallel (AP) in a collinear magnetization geometry. This effect defines spintronics, and has resulted in many advancements in magnetic memory applications and sensors.

In the present work, the GMR ratio is defined as \( (R_{AP} - R_P)/R_P \) where \( R_{AP} \) is the resistance of the AP state and \( R_P \) is the resistance of the P state. GMR is studied for two types of current paths, namely current in the plane of the layer (CIP) and current perpendicular to the plane of the layer (CPP). While CPP measurement requires a lithographically defined path for the current, CIP can be measured on extended films.
In the present work, the CIP GMR measurement is commonly used to check the properties of the deposited material. A modified vision of the CIPT tool (Smarttip) was used to check the GMR on the wafer scale. The CIPT tool provided a wafer measurement stage with the possibility of applying a uniform field to measuring up to 8-inch wafers without the need to breaking the wafer into pieces. This gave us the capability of checking the MR prior to and during device fabrication. The CIPT tip was replaced by a home-made 4 point probe which was connected to a Keithley Instruments 6221 current source and a Keithley Instruments 2182A nanovoltmeter to monitor the resistance while sweeping the field. The Fig. 2.2 shows different parts of this setup. The current is sent from the two outer probes, and the voltages was measured with the two middle probes.

An example of the measurements performed with this setup to check the different processing steps is shown in Fig. 2.3. These tests were performed on a 4-inch wafer with a Pd(8)-Cu(20)-Co(5)-Cu(4)-NiFe-(3.5)-Cu(2)-Pd(2) material stack (all the numbers are nanometer measurements). Since the NiFe (permalloy) field requirement for switching is lower than for Co, this layer switches first, making it possible to see the difference in resistance ($\Delta R$) and to measure the GMR value. Fig. 2.3 (a) shows the measurement on a 4-inch wafer at the center, just after the deposition of the material stack with the AJA sputtering system. From this, one can calculate the GMR to be (0.8%). Afterwards, the wafer was placed into a PECVD system and 30 nm SiO$_2$ was deposited. This step was followed by an RIE of the SiO$_2$ with 20% over-etch. Fig. 2.3 (b) shows the GMR after these two processing
steps; the GMR value can be seen to have increased to 1.1%. We attributed this to the annealing effect from the PECVD deposition. At the same time, the resistance slightly increased, which could be the result of slight oxidation of the cap layers. Fortunately, the switching mechanism was not affected by these processing steps. Fig. 2.3 (c) shows the effect of 30 sec of Ar sputter etch on the wafer. This short plasma etching step is used directly before the deposition of the top contact on the device, in order to remove any oxidation remaining from the processing. As the result of this etching, the resistance increased; this feature is expected, since some of the metallic layers were removed. The consistency in the shape and value of the GMR confirms that the magnetic multilayers were not affected.

2.6 Radio frequency characterization

The schematic of the transmission line used in the present work is shown in Fig. 2.4. The samples were mounted on a suspended rigid aluminum arm located between the two poles of an electromagnet. This arm is then connected to a rotating motor, to give us the freedom of changing the field angle from 0 to 90°. The electromagnet used has a water-based cooling system that give us the capability of bringing the external magnetic field up to 2.1 T. Direct current was provided to the samples using a Keithley Instruments 6221 current source, and the sample voltage was monitored with a Keithley Instruments 2182 nanovoltmeter. The direct contact is then transferred from the transmission line to the devices using GGB industries GSG-40A microwave probes with 150 µm pitch and a maximum operating frequency of 40 GHz. The signal generated was then recorded using a Rohde & Schwarz FSU 67 spectrum analyzer. A Bias-T was used to separate the applied direct current and the generated microwave signal. Since the generated signal is weak and a good portion of the signal will end up below the thermal noise level of the spectrum analyzer, the generated microwave signal is allowed to pass through a low noise
amplifier (gain 40dB, bandwidth 0.1 to 26.5 GHz) after the Bias-T but before the spectrum analyzer. More information regarding the setup and its reflection factor can be found in [62].
Chapter 3

Nano-Contact Spin Torque Oscillator (NC-STO) Fabrication

The NC-STO device geometry is one that brings with it the capability of studying STT-induced magnetization dynamics and spin wave electronics. As their main feature, these devices should have two magnetic materials separated by a nonmagnetic metal, a current path that permits the CPP current configuration, and the capability of sustaining sufficiently high current destiny (i.e., $\sim 10^8$ A/cm$^2$) to allow device functionality. In the present chapter, the fabrication of the NC-STOs studied in this work is briefly explained.

3.1 Active area (mesa)

The active area, or mesa, of the device was made in two different ways. In Fig. 3.1 the first approach is outlined. The fabrication starts on an Si wafer with 1 µm of thermally oxidized SiO$_2$. Then the AJA sputtering system was used to deposit the material stack on the substrate (Fig.3.1(a)). To define the mesa, the first photolithography step was used, and the wafer was spin-coated with resist and exposed with the XLS stepper, to define the pattern of the 8×16 µm rectangular mesa as shown in Fig.3.1 (b). Then with help from an argon plasma (an aggressive physical etching step), the material outside the part covered by the photoresist was removed. Since this etching step requires high-energy argon ions, it can make the photoresist so hard that removal of the resist becomes difficult. The best way to remove resist after aggressive physical etching is by using aggressive oxygen plasma, but for two reasons, this approach cannot be used here. Firstly, in the present work, the material stack is metallic, and this approach can oxidize the mesa and result in inconsistency in performance from device to device. Secondly, the magnetic properties of the FM in the material stack can deteriorate at temperatures above 180°C. Since most of
CHAPTER 3. NANO-CONTACT SPIN TORQUE OSCILLATOR (NC-STO)

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Figure 3.1: Mesa fabrication with Ar sputter etching (a) SiO$_2$ substrate covered by material stack. (b) Photoresist mask used to form the mesa under argon sputter etching.

the systems used for the resist strip cannot control the processing temperature, this approach is not recommended for NC-STO fabrication. Therefore a brief oxygen plasma ashing step was used before putting the wafers into an 80(°C) Microposit Remover 1165 under ultrasonic. Fig. 3.2 shows a fabricated mesa. As can be seen in this SEM picture, on the edge of the mesa there are still traces of the residual resist.

The second processing approach was developed on account of the drawbacks of the first method. Firstly, the resist removal process is difficult and time-consuming,

Figure 3.2: SEM top-view picture of a mesa fabricated using Ar plasma etching. The mesa edges contain residual resist.
and at the same time, the mesa will be exposed to both oxygen plasma and a lengthy resist removal step in the 1165. Secondly, as with all processing tools, the etching system has some downtime, and by replacing this tool, the processing time can be reduced. In this second approach for making the mesa, the material etching step is replaced with a lift-off step, as shown in Fig. 3.3. The processing starts on an Si wafer with 1\( \mu \)m of thermal oxide. The wafer is then coated with a double layer of MicroChem LOR 5A and a positive photoresist (MEGAPOSIT SPR 700-1.2) see Fig.(3.3a). Afterwards, the wafer is exposed and developed, resulting in a mesa pattern with sufficient undercut to guarantee the success of the lift-off, as can be seen in Fig.(3.3) (b). The undercut is employed as the LOR layer is developed faster than the main photoresist. By calibrating the development time, suitable undercut can be achieved. The wafer is then placed in a sputtering chamber and the metallic multilayer is deposited, Fig. 3.3 (b). By removing the LOR resist with help from the 1165 unit, the active area is defined. In this approach, the time required for resist removal is reduced to less than two minutes.

3.2 Insulation layer

Once the mesa has been defined, the material stack needs to be protected against oxidation, while at the same time the current path needs to be defined. Both requirements can be achieved by covering the mesa with an electrical insulation layer. In the present work, 30 nm of SiO\(_2\) is deposited with a PECVD system. The op-
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FABRICATION

Figure 3.4: SiO$_2$ substrate with material multilayer after the definition of the mesa, covered by 30 nm of SiO$_2$.

The optimum temperature for this step of the process is 310(°C) [63]. At the same time, the presence of Co-Cu-NiFe in the material stack limits the processing temperature, since the Cu can diffuse into the neighboring magnetic layers and change their properties, resulting in the degradation of the GMR value. In the present work, temperatures from 300(°C) to 100(°C) were tested, and the quality of the GMR peaks/plateaus and values were recorded. In this way, 180(°C) was determined to be a safe temperature for the process. At this temperature, the GMR value increased. Eventually, a new PECVD recipe was made.

As will be explained in later chapters, the electrical path of the NC-STO is defined in the SiO$_2$ layer. Therefore, it is of great importance to have a high-quality insulation layer to prevent shorting between the mesa and the electrical pads. Also, the thickness of the SiO$_2$ layer defines the breakdown current of the devices. The optimum layer was achieved by fabricating the NC-STO with SiO$_2$ thicknesses of 30 and 60 nm; the devices were made with thicker insulator layer showed substantially lower breakdown currents. In conclusion, in the present work, 30 nm of SiO$_2$ deposited at 180(°C) was used as the insulation layer, as shown in Fig. 2.1.
3.3 Current path

To form the current path, openings should be made in the SiO$_2$ insulation layer. In the present work, the electrical properties of NC-STO are studied using a coplanar waveguide (CPW) fabricated on top of the mesa. In order to fabricate the CPW, three electrical connections to the mesa are required. The middle pad is commonly known as the signal strip, and this is flanked by two micron-sized ground pads. In order to achieve sufficiently high current densities (i.e., $10^8$ A/cm$^2$) a nanosized opening is required under the signal pads. In the following section, the fabrication process of making the nanosized and micron-sized openings in SiO$_2$ is briefly explained.

Hole-mask colloidal lithography (HCL)

This section explains the combination of hole-mask colloidal lithography (HCL) and optical lithography used to fabricate the nanoholes through the SiO$_2$, as shown in Fig. 3.5.

The nanocontact fabrication process steps are as follows: the wafer is spin-coated with Poly(methyl methacrylate) (PMMA), which acts as a mask when the nanoholes are etched out of the SiO$_2$. A short O$_2$ plasma ashing process improved the hydrophilicity of the PMMA. Following this, a polyelectrolyte solution was distributed onto the surface using a pipette, forming negative surface charges that attract the positively charged polystyrene spheres that are later poured as a suspension on top of the PMMA and the polyelectrolyte adhesion layer. The positive charge promotes separation between the spheres, as well as adhesion to the surface. The spheres are suspended in a deionized (DI) water-based solvent rinsed with DI water after two minutes on the surface. Blow-drying with nitrogen is employed to assist DI water evaporation and to avoid rearrangement of the spheres on the surface. Spheres of 40–120 nm in diameter can be utilized with the method, Fig. 3.5 (a). A thin 10 nm chromium film was deposited by e-beam evaporation on top of the spheres, so as to function as a hard mask for subsequent etching of the PMMA (Fig. 3.5 (b)), by first attaching an adhesion tape (Fig. 3.5 (c)) that adheres to the top of the chromium-covered spheres and then removing the tape. A chromium film with a multitude of nanoholes on top of the PMMA is thus produced, Fig. 3.5 (d) [45]. To achieve a limited number of nanoholes (and subsequently, nanocontacts) per device, a second photolithography step was introduced, called a “limiter mask” Fig. 3.5 (e). The wafer was put in a directional oxygen plasma that etches the PMMA anisotropically, forming vertical channels down to the SiO$_2$. Due to the difference in the thicknesses of the PMMA (120 nm) and the photoresist (1500 nm), the photoresist remained during this step, Fig. 3.5 (f). The SiO$_2$ was then etched in an RIE Oxford system with Ar (10 sccm) and CHF$_2$ (20 sccm) plasma, with a total pressure of 30 mTorr and a power of 200 W, Fig. 3.5 (g). This recipe selectively etches the SiO$_2$ without affecting the material stack. Then the PMMA, chromium, and resist were removed.
with the Microposit 1165, leaving nanoholes in the SiO$_2$ film, Fig. 3.5 (h).

Figure 3.5: Nanocontact spin torque oscillator (NC-STO) fabrication
Electron-beam lithography (EBL)

As the second approach to fabricate nanosized openings in SiO$_2$, an EBL system was used. In this approach, the wafer is first coated with ZEP resist—which is a positive EBL resist—and then exposed in an EBL system and developed. The nano-openings in the resist then went through a similar RIE step, as explained in the previous section, to etch the SiO$_2$. After that, the resist was removed with a solution-based removal step.

Using this advanced tool, it is possible to achieve different geometries with high control over the separation and sizes of the fabricated openings. We have managed to fabricate nanocontact as small as 30 nm in a variety of geometries. Fig. 3.6 shows a selection of manufactured nanocontacts. An example of a double 100 nm nanocontact with a center-to-center separation of 200 nm is shown in Fig. 3.6 (a): This type of device was manufactured to investigate how synchronization was affected as a function of nanocontact separation. Devices with nanocontact separation from 160 nm to 1000 nm were manufactured. Fig. 3.6 (b) shows a 100 nm, triple nanocontact arranged in an equilateral triangle, with center-to-center separation of 160 nm. These devices were made to investigate how they interact with each other, and to gain insight into their mutual synchronization. At the same time, it is possible to study the effects of the Oersted field generated by the high-current destiny passing through them. To achieve mutual synchronization in arrays of nanocontacts, the geometries shown in Fig. 3.6 (b–g) were fabricated. For each of these geometries,
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Figure 3.7: SEM image of a mesa with seven nanocontacts and two bottom contacts etched in SiO$_2$.

a selection of nanocontact sizes (30–100 nm) and separations (160 nm to 1000 nm) were manufactured.

Bottom electrode

The current sent through the nanosize opening needs to be collected if the devices are to function as intended. In the present study, this collection is achieved by means of two micron-sized openings in the SiO$_2$ insulation layer, one on each side of the mesa. They are marked as bottom contacts (BCs) in Fig. 3.7. They are rectangular in shape with a size of 2×4(µm$^2$). In the middle of Fig. 3.7, seven NC with a diameter of 100 nm can be seen. The BCs are fabricated with yet another photolithography step, followed by an SiO$_2$ RIE and solution-based resist removal.

3.4 Top contact metalization

For the final step in STO fabrication, we need to produce electrical pads, in order to have the freedom to investigate the devices’ electrical properties. In the present study, coplanar waveguides were formed on top of the mesa. Fig. 3.8 is a SEM picture of the final device; the nanocontact is covered by the signal pad (S). The two bottom contacts on the left, and the one on the right edge of the mesa, are covered by ground pads (G). The inset shows how these are connected to the mesa and the separation between the pads. Since the material used for the top contacts (TCs) is not easily etched with commercial RIE solutions, a lift-off approach is used in the present work. By utilizing a double resist layer of LOR and positive photoresist, and by obtaining the required undercut from the LOR, a TC with a thickness up
3.4. **TOP CONTACT METALIZATION**

The top contact should have the capability of handling current densities as high as $10^8$ A/cm$^2$ and is also expected to have large thermal stability. This current density is obtained at the connection of the nanocontact and the metalization of the TC. To achieve reliable electrical connections, we have investigated different materials for metalization, at different thicknesses. The investigation began with aluminum and gold, yet with these metals at any TC thickness, the devices could not handle the applied current for long. A few minutes after reaching the STO onset current gold TCs would break down. In the case of aluminum the TC would break down even before the STO onset current was reached. By working with metals with higher electromigration resistance and thermal conductivity, the STO performance was improved. The third investigated metal was silver, which is the best thermal conductor. The devices performed very well with 900 nm thick silver TC, and this allowed reliable characterization of the STOs. At the same time, with a thinner Ag TC (500 nm), the STOs broke down a few minutes after reaching their critical current. A much more significant problem with silver TCs was however their mechanical fragility under probing, and small vibrations in the measurement system could easily break them. To further improve the STOs, copper TCs were implemented. Copper is known to have the highest resistance against electromigration, and these devices performed much better than the other tested materials. At the same time, they had better mechanical stability under probing, and for that reason

![Figure 3.8: SEM image from a fabricated device with GSG measurement pads. The inset, in high zoom, shows the mesa and the separation between the GSG pads.](image-url)
they were used in most of the fabricated devices. TCs with different thickness of Cu were tested. The conclusion is that, the thicker the Cu (up to 1000 nm), the higher the breakdown current.

One of the most interesting aspects of STOs is the possibility of studying the generated spin waves with Brillouin-Light-Scattering (BLS) measurements ([64][65]) however requires optical access to the free layer very close to the nanocontact. The TCs shown in Fig. 3.9 were fabricated for this purpose. The nanocontacts are located on the top edge of the S pad, and the difference between the two designs is the metallic area covering the NC. Consequently, for Fig. 3.9 (a), the breakdown current is higher with less optical access, and while the opposite is true for Fig. 3.9 (b). The devices depicted in Fig. 3.9 (b) allow us to measure the generated spin waves with more freedom in three directions.
Part II

Fabricated Spin Torque Oscillators
Chapter 4

Spin Torque Oscillators Fabricated with Hole-Colloidal Lithography

Spin transfer torque (STT) effects have recently been investigated for their potential use in STT magnetic random access memory (STT-MRAM) and STOs. In order to achieve sufficiently large current densities to realize STT effects, nanopillars or nanocontacts with cross-sectional areas of the order of 100 nm are required. The extremely small footprint of the magnetic elements required for STT effects allows for ultra-high storage densities. NC-STOs benefit from a small lateral size and a very wide tuning range of frequency generation, and this makes them ideal candidates for future communication protocols. In spite of this, they suffer from low generated power, which can potentially be solved by mutual synchronization of multiple NC-STOs.

4.1 Spin Torque Oscillator with in-plane fixed and free layers

Fig. 4.1 gives a schematic presentation of the devices used in this study. The material stack consists of a pseudo-spin-valve with an 8 nm Pd seed layer, a 15 nm Cu bottom electrode, a 5 nm Co fixed layer, a 5 nm Cu metallic spacer, a 3 nm permalloy free layer capped with 2 nm of Cu, and 2 nm of Pd used as the device’s active area. As expected from STT-induced oscillators, these devices only function under one current polarity: as shown in Fig. 4.1, they operate only when the electrons reach the free layer first.

In the present chapter, the achievements of fabricating devices with the HCL method are presented as follows: 1. Successful fabrication of single and multiple
CHAPTER 4. SPIN TORQUE OSCILLATORS FABRICATED WITH HOLE-COLLOIDAL LITHOGRAPHY

Figure 4.1: Schematic of an NC-STO with in-plane permalloy (NiFe) free layer and Co fixed layer, separated by Cu. The structure also has a Pd(5 nm)-Cu(10 nm) seed layer and is capped with Cu(2 nm)-Pd(2 nm). In the measurement, the electrons reach the NiF layer first

NC-STOs. 2. Mutual synchronization of double and triple NC-STOs. 3. Pairwise synchronization in devices with four and five NCs. 4. Vortex dynamic in signal NC devices.

4.2 Fabricated geometries

As explained in the section on fabrication, to make nanosized openings, a combination of HCL and the photolithography technique is used. Here we present the NCs obtained through this fabrication method. First, in Fig. 4.2 (a), one can see a SEM image of a top HCL mask with the chromium hard mask covering the PMMA resist. This shows that the distribution of the holes is random. Therefore, the number of NCs will be different for each mesa. However, the distances between holes are rather uniform; they are spaced between 80 and 100 nm for a 100 nm sphere. Fig. 4.2 (b–e) shows examples of how this process leads to one to four equally spaced nanoholes in the SiO2. In Fig. 4.2 (c), a double nanocontact is formed with a 0.5\mu m limiter. The holes have a diameter of 100 nm and an edge-to-edge distance of 100 nm. The final device is shown in Fig. 4.2 (f). The top and bottom contacts are created by a lift-off pattern and the evaporation of 1 \mu m silver. The central signal pad (S) is connected to the HCL holes on top of the mesa. The contact has
4.2. FABRICATED GEOMETRIES

Figure 4.2: SEM images. (a) top view of chromium and PMMA mask. (b)–(e) single, double, triple, and quadruple 100 nm nanoholes made through the SiO$_2$ insulation layer (f) Final device layout with top contact waveguide for microwave measurements: Signal (S) and two ground (G) pads are shown in the picture.

a ground-signal-ground (GSG) geometry to minimize microwave losses.

The degree of achievable multi-nanocontact control is presented in Fig. 4.3, which shows the distribution of nanocontacts for different diameters of the limiting mask, and for two different concentrations of the suspension. 18 nanocontact-STO devices were analyzed for each fabrication condition. At the highest concentration of

Figure 4.3: Distributions of the number of nanocontacts as a function of limiting mask diameter. (a) high concentration (0.04% w/v) of 80 nm spheres, (b) low concentration (0.02% w/v) of 80 nm spheres, (c) low concentration (0.02% w/v) of 100 nm spheres. Legend denotes the diameter of the limiting mask. Insets show the mean number of nanocontacts vs. the limiting mask diameter. Error bars indicate the full range of the data set.
spheres, the smallest limiter (0.45 \( \mu \text{m} \)) results predominantly in double NCs (55%) with some fraction of both single (28%) and triple (17%) nanocontacts. As the size of the limiting mask is increased, the number of nanocontacts per device increases, with the largest opening (of 0.8 \( \mu \text{m} \)) yielding devices with over 10 NCs. As can be seen in Fig. 4.3(b)–(c), a lower concentration of spheres shifts the distributions to fewer NCs per device. For example, in Fig. 4.3(c), the smallest limiter (0.5 \( \mu \text{m} \)) results predominantly in single nanocontacts (55%), and one fifth of all devices are without nanocontacts altogether.
4.3 Mutual synchronization

All the devices with one or more NCs showed microwave signals under sufficiently large applied current when an external field of 1 T was applied 70° from the film plane. The resulting microwave frequency is about 20 GHz under these conditions. Fig. 4.4 shows power spectral-density color maps as a function of applied direct current for NC-STO’s with signal, double, and triple NCs. Extraction of the onset current from these devices results in an onset current range of 15–17 mA for each NC, or a $2 \times 10^8$ A/cm$^2$ current density. These values also hold for devices containing more NCs (these are shown in the next section), indicating that the onset current for oscillation increases linearly with the number of NCs. Consequently, the critical current density is not dependent on the number of NCs.

Fig. 4.4 (b–c) shows the integrated power and linewidth extracted from single NC-STO, Fig. 4.4 (a). The maximum power of 90 pW with linewidth as low as 10 MHz was achieved at 28 mA. The synchronization in double and triple NC-STOs is also achieved at the same current density ($3.2 \times 10^7$ A/cm$^2$), with a strong increase in the power and a reduction in the linewidth Fig. 4.4. The lowest linewidth (of 5 MHz) recorded was for the synchronized triple NC device.

Fig. 4.4 (f) shows the current dependence of the microwave power in a double NC system. The power reaches its maximum at the center of the synchronized region, and sinusoidally falls off when it approaches either minimum power limit. By extracting the power generated from each NC ($P_1 = 17$ pW and $P_2 = 45$ pW), and by using the equation (4.1) \cite{72}, one can calculate the total maximum power by putting $\cos(\delta) = 1$. The calculated power is 117 pW, which is close to the measured maximum power. By assuming a linear current dependence of the relative phase shift, one can fit the sinusoidal behaviors of the power, as demonstrated with the purple fit in Fig. 4.4 (f). Therefore, the assumption of a linearly dependent phase shift is reasonable, as the frequency of the two independent signals, and also of the synchronized signal, all depend linearly on the current.

$$ P_{tot} = P_1 + P_2 + 2\sqrt{P_1P_2} \cos(\delta) \quad (4.1) $$

$$ P_{tot} = P_1 + P_2 + P_3 + 2\sqrt{P_1P_2} \cos(\delta_{1,2}) + 2\sqrt{P_1P_3} \cos(\delta_{1,3}) + 2\sqrt{P_2P_3} \cos(\delta_{2,3}) \quad (4.2) $$

In principle, equation (4.1) can be expanded for multiple NC systems, but this requires knowledge of the relative phase between the different oscillators. In contrast, to calculate the maximum power in a three NC-STO system, we can assume that they are all in phase, and thus that $\cos(\delta) = 1$. By extracting the power value
from Fig. 4.4 (i) \( P_1 = 7.0 \text{ pW}, \ P_2 = 1.7 \text{ pW}, \ \text{and} \ P_3 = 1.4 \text{ pW} \) and using equation (4.2), we can calculate the maximum power to be 26 pW. However, the maximum value of 47 pW is reached in this measurement, which is almost twice as large as predicted. This may be even larger, since the system cannot sustain higher currents to confirm the maximum power. We attribute this to distinctive interaction between the individual NCs before synchronization, which reduces the power level before approaching synchronization.

4.4 Pairwise synchronization

Complete mutual synchronization of devices with 4 and 5 NCs was not observed in the current study. In contrast, pairwise synchronization was seen in many cases, with an increase in power and a decrease in linewidth. Fig. 4.5 (a and d) show two

Figure 4.5: Spin-torque oscillator signal properties as a function of current. Devices with 4 (a–f) and 5 (g–i) nanocontacts showing pairwise synchronization. The labels in (a, d, g) refer to the colors used in the linewidth and power plots.
4.4. PAIRWISE SYNCHRONIZATION

devices with 4 NCs, and in both cases the signals interact strongly with each other and become locked and unlocked. For example, in Fig. 4.5 (a), this occurs between 65 and 78 mA for the higher frequency mode (black), while for the blue and red modes, synchronization was observed between 67–75 mA, and the power shows a cosine-like current dependence behavior.

The lack of complete mutual synchronization in devices with more than three NCs can be explained by two effects. Firstly, as was observed for double and triple NC-STOs, synchronization begins at a current density of around $3.2 \times 10^8$ A/cm$^2$. For devices with more than three NCs, reaching this current density would destroy them. Synchronization is thus unachievable. The maximum current density is reduced as the NC number is increased. For single NC devices, the maximum current density before device failure is around $4.5 \times 10^8$ A/cm$^2$, while for devices with 2 and 3 NCs, this number is reduced to $3.8 \times 10^8$ A/cm$^2$ and $3.4 \times 10^8$ A/cm$^2$, respectively. This reflects the fact that, to a some degree, it is also the total current and not only the current density that governs device failure due to heating. Consequently, when devices with 4 NCs reach $2.5 \times 10^8$ A/cm$^2$, they experience breakdown, and hence can never reach the current density required for complete synchronization. Secondly, it is quite likely that the random orientation of NCs favors pairwise synchronization, and that a better defined ordering of these geometries is required to achieve mutual synchronization.

Figure 4.6: Vortex dynamic of a single 100-nm NC under zero applied field: (a) current scan (b) extracted linewidth (c) integrated power.
4.5 Gyrotropic vortex motion

The NC-STOs fabricated in this study can also sustain gyrotropic vortex motion [73, 74], with generated frequencies below 1 GHz, and are capable of operating under zero applied magnetic field [75]. While the details of the gyrotropic vortex motion have not been studied in depth in HCL fabricated devices, we here present an example of such operation. Fig. 4.5 (a–c) shows the operation of an NC-STO with a single 100-nm NC under zero external field. The device shows multiple harmonics and a weak current tunability of 5.6 MHz/mA between 5 and 15 mA, which changes to 37 MHz/mA for a current regime of 15–30 mA. The lowest linewidth of 6 MHz was recorded at 6 mA, located in the low current tunability part, and the linewidth increases to 30 MHz in the second regime. The integrated power of this type of oscillation is known to be much larger than the high frequency mode [76]. While the power of the high frequency mode barely reaches 100 pW (as shown in the previous section), the integrated power of the vortex motion in the same device is almost 25 nW 4.5 (c).

4.6 Conclusion and summary

In conclusion, we have demonstrated a new, versatile way of fabricating NC-STO with high-quality, single and multiple, 100 nm and 80 nm nanocontacts. The manufacturing method presented here is capable of producing devices with NCs down to 20 nm in diameter. The manufactured devices demonstrated mutual synchronization in up to 3 NCs, and pairwise synchronization of devices with 4 and 5 NCs. The fabricated devices are also capable of showing gyrotropic vortex motion, and can be used for studying parallel connected multivortices. We believe the new manufacturing technique can speed up the NC-STO improvements and produce complete synchronization in large arrays of NC-STOs, and will also allow the study of different types of dynamics, such as gyrotropic vortex motion, in such devices.
Chapter 5
Spin Torque Oscillator with Perpendicular Magnetic Anisotropy

Early work in STOs and NC-STOs focused on the dynamics of magnetic thin films with in-plane (IP) magnetization, and out-of-plane (OOP) dynamics were also studied by applying OOP magnetic fields \[16\]. Recently, it has been demonstrated that devices with an IP polarizer and a \([\text{Co/Ni}]\) PMA free layer can generate coherent OOP precession and microwave signals, with power as high as 1 nW \[48\]. The dynamics of these two geometries are very different, and the field required for the operation of NC-STOs with PMA free layers is much lower than for devices with traditional IP free layers. Consequently, the fixed layer is rotated much less, which makes these devices suitable for studying STT-induced dynamics. In this chapter, we have focused on implementing a material stack with a high-PMA free layer and an IP fixed layer into NC-STO devices in order to study the dynamic of these geometries in depth.

5.1 Spin-torque oscillators with in-plane fixed layers and PMA free layers

In the present study, the orthogonal spin valve (Ortho-SV) shown in Fig. 5.1 was fabricated into an NC-STO. The fixed layer for this geometry has IP magnetization, while the free layer is a PMA layer. The fixed layer is made from Co, which is a material with high spin torque and spin polarization. The PMA free layer is made from \([\text{Co/Ni}]\) multilayers \[48\], and has high spin torque and also spin polarization \[77\]. At the same time, the saturation magnetization and anisotropy can be easily tuned, e.g., via the Co and Ni thickness or the number of repetitions. This makes the material a suitable candidate for such devices. Furthermore, the
CHAPTER 5. SPIN TORQUE OSCILLATOR WITH PERPENDICULAR MAGNETIC ANISOTROPY

Figure 5.1: Schematic demonstration of an Ortho-NC-STO with PMA [Co/Ni] free layer and in-plane fixed layer. This structure has a cap layer of Cu(2 nm)-Pd(2 nm) and has a Ta(5 nm)-Cu(10 nm)-Ta(5 nm) seed layer.

fabricated devices are only operational under one current polarity, namely when the electrons are entering the material stack and reaching the free layer first, and later coming to the fixed layer, as is shown in Fig. (5.1).

The fabricated devices revealed two interesting futures that are presented in the following sections. Firstly, they operate at much higher frequencies than previously reported in [48], and under almost zero applied field. Secondly, the system proved an excellent medium for generating and studying the rich dynamics of magnetic droplet solitons.

5.2 Low applied field operation

As suggested by [48], the generated threshold frequency \( f \) in an NC-STO with a PMA free layer is governed by

\[
f = \frac{\gamma \mu_0}{2\pi} (H + (H_k - M_s) \cos(\theta))
\]

where \( \gamma \) is the gyromagnetic ratio, \( H \) the external field, and \( \theta \) the free layer precession angle. According to this equation, there are three possible ways of increasing the generated frequency. Firstly, the external magnetic field can be increased to raise the generated frequency, but as has been explained, this approach is not applicable in real device applications. However it is possible to increase the operation frequency by increasing the PMA and/or by decreasing \( M_s \). The latter option is used in the present study to increase the operation frequency under low applied field.

The free-layer magnetization saturation of the Ortho-NC STO used in the present study is approximately \( \mu_0 M_s = 0.9 \pm 0.05 \text{ T} \), which is slightly lower than the
5.2. LOW APPLIED FIELD OPERATION

Figure 5.2: (a) IP and OOP magnetoresistance field sweep (b) AGM magnetization on extended thin film with Ortho-SV. The inset presents the high-field scan.

value of 1.04 T calculated from the bulk magnetization of nickel and cobalt. The parameter that defines the operation frequency in this device is \( H_K - M_s \). To extract this value from the manufactured MLs, a comparison of the M-H loop and MR loop

Figure 5.3: Current scan and Ortho-NC-STO with 65-nm NC under 0.2 T external applied field. The inset shows threshold frequency as a function of applied field for two devices with 63-nm and 65-nm NCs.
CHAPTER 5. SPIN TORQUE OSCILLATOR WITH PERPENDICULAR MAGNETIC ANISOTROPY

is made, as shown in Fig. 5.2. The saturation field of $\mu_0 H_{sat} = \mu_0 (H_k - M_s) = 0.35$ T can be estimated from these loops. This was extracted from the linear response in MR and the shear free layer loop in M-H, shown as a green dashed line in Fig. 5.2 (a,b). The inset of Fig. 5.2 (b) shows the magnetization loop in a higher field.

Fig. 5.3 shows the power spectral density color map as a function of direct current for an Ortho-NC-STO under a 0.2 T perpendicular external applied field for a device with a 65-nm NC. As can be seen, the generated frequency decreases from 18 GHz to almost 16.5 GHz as the current increases. The inset shows the onset frequency for two devices with NC sizes of 65 nm and 63 nm as a function of applied external field, with minimum generated frequency of 12 GHz under a 0.02 T perpendicular applied field.

5.3 Observation of dissipative droplet solitons

Dissipative magnetic droplet solitons are highly nonlinear, nano-magnetic, and dynamic objects and are closely related to the conservative magnon droplets pre-

![Figure 5.4](image.png)

Figure 5.4: NC-STO with in-plane Co fixed layer and perpendicular [Co/Ni] free layer and strong PMA. The applied field tilted the Co layer out of the plane. Droplet formation is shown in cross-section. The arrows and circles show the formation of the droplet in the PMA free layer, starting from the top.
5.3. OBSERVATION OF DISSIPATIVE DROPLET SOLITONS

Figure 5.5: Perpendicular external field scan on an NC-STO with a 63-nm NC under fixed (-6 mA) biased current. From top to bottom are shown: frequency spectral density, integrated power, and MR as a function of perpendicular applied field. An FMR-like mode is observed between 0.1 T and 0.65 T, with a slope of 28.7 GHz/T. At $\mu H_{\text{drop}} = 0.65$ T, the droplet forms with a 10.3 GHz drop in frequency, modulation sidebands appear, and the integrated power increases from 5 pW to 200 pW. The MR decreases linearly by -0.25%/T, down to the droplet formation field, which is corroborated with a 0.1% jump and a change to a positive linear slope of (0.17%/T).
dicted by Ivanov and Kosevich in 1997 \cite{50,51}. They have not been experimentally confirmed before the present work. Recently, theoretical work by M. Hoefer et. al. \cite{49,78,79} showed that NC-STOs with free layers with sufficiently high PMA should be able to support magnetic droplet solitons, and these devices provide an environment that permits the study of the interesting dynamics of droplets. This thesis presents the experimental observation of localized dissipative droplets in an Ortho-NC-STO, as introduced in the last section.

Fig. (5.4) gives a simplified schematic picture of magnetic droplet formation. The magnetic droplet is generated underneath the NC when a direct current is applied. The magnetization of the droplet is opposite in direction to that of the far region of the free layer outside the NC. All the spins throughout the entire droplet precess with the same frequency, but the precession angle is a decreasing function of the radial distance from the center of the NC, and approaches zero well outside the NC.

For experimental observation of the droplet, the Ortho-NC-STO with an NC size of 63 nm was biased under a fixed direct current (of -6 mA), while the perpendicular external field was scanned from zero to 1.2 T, as shown in Fig. 5.5. At low applied field, the device shows a linear FMR-like dependence, as was also demonstrated in \cite{48,69}. However, at $\mu_0 H_0 = 0.65$ T, the generated frequency drops dramatically (by 10.3 GHz) to a frequency well below that of FMR. At the same time, the integrated power increases dramatically by a factor of about 40. The observation of side bands for the droplet was unexpected, since this device was measured under direct current, and no modulating RF signal was applied \cite{24,25}. Therefore the modulation must be an intrinsic property of these devices, and we refer to this observation as “automodulation”.

The bottom panel in Fig. (5.5) shows the MR value during the field scan for two different currents (-1 mA and -6 mA). For field values less than 0.65 T, the MR decreases linearly for both currents, which is consistent with a linear increase in the fixed layer’s perpendicular magnetization component. While the -1 mA scan does not show any change over the full field scan, the -6 mA scan, exhibits a jump of 0.1% at the transition field, and the MR slope changes sign. The jump in the resistance is related to the free layer spins that suddenly point more antiparallel against the fixed layer spins. And the positive slop in the resistance after droplet formation is explains as follows: After droplet formation the fixed layer magnetization rotates OOP as the external field increases which results in increasing antiparallel alignment between free and fixed layer magnetization and consequently higher resistance.
5.4 AUTOMODULATION IN DROPLETS

Figure 5.6: Current sweep for Ortho-NC STO under perpendicular applied field (0.8 T), showing a FMR-like signal at low current and the formation of (a) a droplet with automodulation at 6 mA for a 63-nm NC, and (b) a droplet without automodulation at 12.5 mA for a 110-nm NC.

5.4 Automodulation in droplets

As mentioned earlier, the droplet dynamic showed a modulation signature when the devices were biased with direct current alone, and for this reason, we refer to this as automodulation and consider the effect as an intrinsic property of droplets. Fig. (5.6)(a) shows the current sweep for two devices with NC sizes of (a) 63 nm and (b) 110 nm, under fixed external field (0.8 T). In both devices, below the critical current for droplet formation, an FMR-like mode is observed, at 5.9 mA and 12.5 mA for NC sizes of 63 nm and 110 nm, respectively. It is evident that only the device with the smaller NC shows the automodulation. Automodulation effect was only observed for devices whose NC size was less than 90 nm. The automodulation may be a result of droplet drifting and restoring in a periodic fashion that generates additional low frequency signal that combines with droplet frequency.

5.5 Breathing in droplets

Fig. (5.7)(a) shows a current scan under an applied field of 0.8 T at an angle of 30° from the film plane, for a device with NC size of 63 nm. In this measurement, the droplet is formed at 3 mA and, as the current increases to 6 mA, two other modes are recorded at 1/2 and 3/2 of the droplet frequency. With help from theory and micromagnetic simulation, these can be identified as “breathing” modes that result from the periodic formation of the droplet. The breathing can also be observed under perpendicular applied field (not shown here). Fig. (5.7)(b) shows the result of micromagnetic simulation and presents a period of breathing for an 80-nm NC-STO
CHAPTER 5. SPIN TORQUE OSCILLATOR WITH PERPENDICULAR MAGNETIC ANISOTROPY

5.6 Conclusion and summary

In this chapter, NC-STOs with in-plane fixed layer and strong PMA, as well as free layers of [Co/Ni] ML, were fabricated. Under low applied field (0.02 T), these devices generated frequencies of 12 GHz, as predicted by theory. Moreover, these devices under an applied field larger than 0.4 T revealed evidence of droplet formation. This was predicted long ago, but this is the first experimental observation. The dynamics of these modes, as expected, contain a variety of interesting and complicated nonlinearities, such as automodulation and breathing.
5.6. CONCLUSION AND SUMMARY
Chapter 6

Single Layer Nanocontact Spin-Torque Oscillator

As mentioned earlier, NC-STOs work on the basis of STT and GMR \[12\] or TMR \[13\] effects. Therefore, the material stack for fabricating NC-STOs, requires at least two ferromagnetic materials separated by a nonmagnetic metal (in the case of GMR), or an electrically insulator layer (for TMR). Consequently, the fabrication of the material stack is one of the parts that makes device manufacturing complicated. Early studies of point-contact and nanopillar STOs showed that an unpolarized current traversing a FM layer can induce enough STT to cause instability detectable in resistive measurements \[54,55,80\]. Theory predicts that the spin filtering at the interface of a FM and a nonmagnetic metal creates spin accumulation \[56,81,82\], which leads to a sufficiently strong torque to produce a spin wave instability in the FM. While for symmetric interfaces, the net torque will be zero, any asymmetry between interfaces will generate a considerable amount of torque.

In the present chapter, the material stack consists of only one FM layer implemented in the NC-STO. We have studied the device’s microwave properties as a function of current, and applied in-plane external magnetic field. For the first time, STT-driven dynamic has been observed. The microwave signal is present under zero applied field with strong current hysteresis.

6.1 Device layout

Fig. 6.1 shows a schematic of the device layout under investigation. The material stack consists of a Pd (5 nm) seed layer, a Cu (20 nm) bottom electrode, and an NiFe (7 nm) active area, capped with Cu (2 nm) and Pd (2 nm). The devices produce a microwave signal when the electrons pass from the NC and reach the top NiFe interface first, as depicted in Fig. 6.1. The magnetic properties of the full stack were determined using a PhaseFMR system, yielding a saturation magnetization of
1.09 T and in-plane anisotropy field of 7 Oe.

6.2 Zero applied field operation

In this section, a single 100-nm NC-STO is studied under zero applied field. Fig. 6.2 (a) shows a typical drive current scan at zero applied external field. The current scan begins at +2 mA and goes down to -35 mA, before returning to +2 mA. The generated microwave signal is strongly hysteretic with current, and no microwave signal is present to -32 mA. At this current (onset current), a microwave signal appears at about 3 GHz. The generated frequency stays constant with almost no change as far as -35 mA. When the current is decreases, the frequency also decreases almost linearly to 250 MHz at -13 mA, before the signal disappears. The current scan shows a number of weak mode transitions. The inset in Fig. 6.1 (a) shows the measured spectrum at -15 mA; it is possible to observe up to five harmonics, with the even harmonics being generally stronger than the odd ones.

In the present study the generated signal has much higher frequency than the gyrotropic vortex oscillation (500 MHz) [83] and consequently such mechanism cannot explain the observed signals. On the other hand, it is possible to relate the present dynamics to the numerically observed vortex-antivortex (V-AV) creation and annihilation [84,85] dynamics. The frequency range and the strong quasilinear current dependence are consistent with V-AV creation and annihilation processes. According to numerical simulations [84], the Oersted [86,87] field and the spin-transfer torque nucleate a V-AV pair, with the antivortex being essentially motionless. The
6.2. ZERO APPLIED FIELD OPERATION

Figure 6.2: Device operation under zero applied field: (a) Current scan from +2 to -35 mA and back to +2 mA for a device with a 100-nm NC. The inset shows the power spectral density at -15 mA, where up to 5 harmonics can be observed; (b) linewidth vs. current extracted from the -30 mA to +2 mA current scan.

A mobile vortex then oscillates, generating a new V-AV pair with opposite polarity. The first V and the second AV then annihilate, generating spin waves, leaving a new V-AV pair but with opposite polarity to the original pair. The process can now
When the current is reduced below the V-AV nucleation current, then the linewidth improves dramatically, as shown in Fig. 6.2 (b). While it is beyond the scope of the present work, this dynamic is very similar to that of a GMR-based NC-STO [73], which could be attributed to a moving vortex in the absence of V-AV creation and annihilation, and is consistent with vortex polarity switching at threshold [74,88,89].

The linewidth of the strongest mode is shown in Fig. 6.1 6.2 (b), and reaches values as low as 6 MHz at -18 mA for a frequency of about 700 MHz, while the frequency vs. current also shows a linear dependency with a slope of 150 MHz/mA.

### 6.3 In-plane field dependence

The field dependence of the NC-STO is also studied here as a function of in-plane external field. In the inset of Fig. 6.3, the onset and cut-off currents are plotted as a function of in-plane applied field, and both increase linearly. The in-plane field

---

**Figure 6.3:** In-plane field dependence of the generated microwave signal. Inset: Onset and cut-off current of microwave signal as a function of in-plane applied field.
promotes uniform magnetization of the permalloy layer, and as the result larger Oersted field (higher DC current) is required to nucleate the V-AV pair. At high enough field strengths (60 Oe), our maximum driven current is no longer large enough to nucleate the V-AV pair, and consequently no dynamic can be observed.

The field dependence of the generated microwave signal is shown in Fig. 6.3. The frequency decreases as the in-plane field increases, though the power and linewidth behavior remain the same. One might expect that by applying an in-plane field, the total energy of the system would increase, and that consequently so would the frequency. But according to the numerical simulation presented in [90], the V-AVs are not exactly centered in the NC and so the system is not symmetric, which may very well reduce the V-AV potential well, and result in a reduction in the frequency—as we have observed experimentally and depict in Fig. 6.3. The small mode changes are also shifted to higher current, as a function of applied in-plane field.

6.4 Conclusion and summary

In conclusion, a NC-STO with material stack consisting of a permalloy sandwiched between two copper electrodes with different thicknesses was successfully fabricated. The generated microwave signal from devices with a 100-nm NC was presented. These devices can produce frequencies between 250 MHz and 3 GHz under zero applied field. The microwave signal shows a high degree of coherence, with up to five visible harmonics. The dynamic is argued to be initiated as a result of a vortex-antivortex creation and annihilation mechanism, which possibly can be changed to vortex core switching dynamics. The in-plane field dependence shows that, as the field increases, the generated frequency decreases and the onset and cut-off current increase, until the dynamic is completely suppressed at 60 Oe.
Chapter 7

Conclusions and future works

The research presented in this thesis mostly focused on the fabrication of nanocontact spin-torque oscillators (NC-STOs). The main focus was the manufacture of NC-STOs using hole-colloidal lithography (HCL). Afterwards, a variety of NC sizes and geometries were implemented in NC-STOs with different materials stacks. In the following, we list the results from the fabricated NC-STOs:

From devices fabricated with the HCL method:

1. By combining hole-colloidal lithography with optical lithography, nanocontact spin-torque oscillators with nanocontact sizes of 100 and 80 nm were successfully fabricated. Using this method, NC-STOs with single and multiple nanocontacts were successfully manufactured.

2. The fabricated devices show both gyrotropic vortex-type dynamics under zero external applied field, and also high-frequency operation under perpendicular and slightly tilted external fields.

3. For the first time, mutual synchronization of three parallel connected NCs was observed. Pairwise synchronization was demonstrated in NC-STOs with four and five nanocontacts.

From Orthogonal NC-STOs:

1. Devices fabricated with a [Co/Ni] multilayer free layer showed operation at 12 GHz in weak applied fields (e.g. 200 Oe). We have also shown that, by increasing the perpendicular magnetic anisotropy (PMA), the operational frequency could be increased compared to previous reports in the literature.

2. As was theoretically predicted, magnetic droplet solitons were observed in NC-STOs with strong PMA free layer.

3. The magnetic droplet showed automodulation as an intrinsic property in devices with nanocontacts smaller than 90 nm. This automodulation originated
from periodic displacement of the droplet core under the influence of the effective field.

4. Two interesting modes, at $1/2$ and $3/2$ of the droplet frequency, were observed. With help from micromagnetic simulations, they were attributed to droplet breathing.

From single-layer NC-STOs:

1. NC-STOs with only one permalloy layer as the ferromagnetic material in the multilayer were fabricated. They produced microwave signals between 250 MHz and 3 GHz under zero applied field.

2. This effect was attributed to vortex core switching or vortex-antivortex annihilation and recreation.

3. The device operation was strongly affected by in-plane magnetic fields.

This work has contributed to the techniques for fabricating NC-STOs and has produced a platform for further exploration of this technology. Many of our findings are entirely new in orthogonal NC-STOs and single-layer NC-STOs and some presently lack a complete physical explanation. Thus, much investigation and experimental work remains for future research.

**Future work**

The fabrication of the devices using hole-colloidal lithography can be further improved. This technology has the capability of making NCs as small as 10 nm, and this has yet to be demonstrated. The functionality of these devices is limited, due to the high current density required and the heating that results. Investigation into different materials in various top contact geometries has the potential to overcome these limitations in the future.

The operational frequency of the NC-STOs can be further increased in three ways: firstly, by implementing a free layer with a higher PMA value (for example, PMA MnGa has shown an FMR of 300 GHz [91]). Secondly, by decreasing the NC size to 10 nm. Finally, by increasing the saturation magnetization of the fixed layer, hence it requires larger external field tilts and does not gives enough perpendicular STT contribution to form the droplet, therefore, it is still possible to observe the FMR like frequency even at larger field than we used in this study.

As current theory suggests [78], a magnetic droplet solitons may propagate up to 10 $\mu$m in a low damping medium. Fabrication of devices capable of investigating this theory would be of great interest. One could the also study the interaction of two or more droplets sharing the propagating medium as a function of spacing in
different material systems.

Single layer NC-STOs have opened the door to new systems which have not yet been explored in depth. The origin of the observed dynamics is not known at present, and the behavior of these devices under perpendicular fields is very complex, involving interactions between many generated modes. In the present work, single-layer NC-STOs made with permalloy were briefly investigated, and many other material system, such as PMA [Co/Ni], can be implemented in future. These devices can be used for magnonics and for studying the generated spin waves in a medium that is not affected by the fixed layer.
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