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RPPR Final Report
as of 13-Sep-2022

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Proposal Number: 70740EMDRP

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Final Report for Period Beginning 01-Feb-2017 and Ending 15-May-2022

Title: Magnetic Thick Films for Integrated Microwave Devices

Begin Performance Period: 01-Feb-2017

End Performance Period: 15-May-2022

Report Term: 0-Other

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STEM Degrees: 0

STEM Participants: 1

Major Goals: THRUST 1: Self-Biased Microwave Materials from Nanoparticle Precursors: The objective of this thrust is to develop new fabrication approaches for realizing ultra-thick (up to 200 um), high-performance, patterned hexaferrite films on semiconductor substrates.

THRUST 2: Integrated Bias (Permanent) Magnets: The focus of this trust is to develop thick-film (up to 200 um) CoPt and FePt micromagnets on semiconductor substrates to serve as high-performance bias magnets for integrated magnetic components.

THRUST 3: Integrated Magnetic Components: The objective of this thrust is to design, microfabricate, and test non-reciprocal circulator devices as test vehicles for highlighting the feasibility of integrated magnetic microwave and mm-wave component technologies.

Accomplishments: See attached report.

Training Opportunities: Nothing to Report

Results Dissemination: See attached report.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: David P Arnold
Person Months Worked: 1.00

Funding Support:

Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
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Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Hae-In Kim
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Leili Hayati
Person Months Worked: 4.00 **Funding Support:**
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ARTICLES:

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Journal: Journal of Microelectromechanical Systems
Publication Identifier Type: DOI Publication Identifier: 10.1109/JMEMS.2018.2888846
Volume: 28 Issue: 2 First Page #: 311
Date Submitted: 8/6/19 12:00AM Date Published: 4/1/19 4:00AM
Publication Location:
Article Title: Ultra-Thick Electroplated CoPt Magnets for MEMS
Authors: Yuzheng Wang, Jacob Ewing, David P. Arnold
Keywords: Electroplating, CoPt, magnetic materials
Abstract: This paper reports the fabrication and magnetic characterization of very thick (50+ ?m) and high-performing (coercivity up to 850 kA/m; energy products up to 75 kJ/m^3) electroplated permanent magnets microfabricated on silicon substrates. Intended for MEMS applications, the fabrication process yields higher areal magnetic energy density (5.6 J/m2) and faster plating rates (42 ?m/h) compared with previously published work. Four main accomplishments are reported: 1) optimization of the underlying seed layer metallurgy to improve film adhesion and inhibit interfacial diffusion/reactions; 2) development of a warm-bath (50 °C), high-current-density (300-2000 mA/cm^2) electroplating process that dramatically increases plating rate while maintaining good magnetic properties; 3) study of the electroplating bath longevity; and 4) exploration of the nanostructure of the electroplated magnets by TEM/STEM.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Transactions on Microwave Theory and Techniques
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Volume: 67 Issue: 8 First Page #: 3230
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Article Title: Investigation of Ferromagnetic Resonance Shift in Screen-Printed Barium Ferrite/Samarium Cobalt Composites
Authors: Camilo Velez, Seahee Hwangbo, Stasiu T. Chyczewski, Jacob Ewing, Renuka Bowrothu, Connor S. Sm
Keywords: Barium hexaferrite, microfabrication, millimeter wave, samarium cobalt, screen printing
Abstract: This paper explores a method for incorporating samarium cobalt (both Sm2Co17 and SmCo5) inclusions into screen-printed barium hexaferrite (BaFe12O19) films in order to tune the ferromagnetic resonance (FMR). Using an all-low-temperature screen-printing process, >140-?m-thick composite films are fabricated using heterogeneous mixtures of magnetic particles in a polydimethylsiloxane (PDMS) binder. RF characterization is performed using two-port S-parameter measurements on a coplanar waveguide (CPW) with external magnetic bias fields. The films exhibit a self-biased FMR response that ranges from 41 to 53 GHz (12-GHz span) by varying the relative ratio of the hexaferrite and Sm-Co particles. These effects are attributed to the embedded Sm-Co particles providing additional internal field bias acting on the barium ferrite.
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Article Title: Patterning of thick electroplated CoPt magnets using SU-8 micromoulds
Authors: Yuzheng Wang, Renuka Bowrothu, Yong-Kyu Yoon, David P. Arnold
Keywords: cobalt platinum, SU-8, electroplating
Abstract: Recently, electroplated cobalt platinum (CoPt) magnetic films have been developed that afford thick (up to ?100 ?m), high-energy-density (up to ?100 kJ/m3) permanent-magnet microstructures. However, the aggressive electroplating conditions have shown to be incompatible with most thick-film photoresist mould materials, making patterning these films an unanswered technical challenge. In this work, it is reported a complete process flow of fabricating and removing SU-8 photoresist moulds to enable the ultra-thick patterned CoPt magnets on silicon wafers. The implementation of thick SU-8 2050 electroplating moulds makes it feasible to deposit 100 ?m thick CoPt magnets in 4 h. A 25 nm thick sputtered titanium layer is used as a sacrificial layer to completely release the SU-8 mould in hydrofluoric acid after electrodeposition. Compared to prior research, significantly improved pattern definition and constant magnetic performance are observed and characterised by optical profilometer, scanni
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Volume: 68 Issue: 12 First Page #: 5065
Date Submitted: 8/17/21 12:00AM Date Published: 12/1/20 5:00AM
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Article Title: 35-GHz Barium Hexaferrite/PDMS Composite-Based Millimeter-Wave Circulators for 5G Applications
Authors: Renuka Bowrothu, Hae-In Kim, Connor S. Smith, David P. Arnold, Yong-Kyu Yoon
Keywords: Barium hexaferrite (BaM) and polydimethylsiloxane (PDMS) composite , dielectric loss , fifth generation (5G) , Ka-band , low profile , packaging compatible , roughness effect , screen printing , self-biased circulator
Abstract: We report a self-biased, low-profile circulator operating in the Ka-band fabricated by an entirely low-temperature (70 °C) screen-printing approach on printed circuit board (PCB). The magnetic material for the circulator is a barium hexaferrite BaFe12O19 (BaM)/polydimethylsiloxane (PDMS) nanocomposite that exhibits a zero-bias ferromagnetic resonance frequency (f FMR) at 46.6 GHz. Using this material, a microstrip-based circulator operating at 35 GHz is designed, fabricated, and characterized. A combination of mechanical milling, screen printing, photolithography, and electroplating is used for fabricating the circulator, in which the circulator disk (diameter of 2 mm and thickness of 250 ?m) is completely embedded in the PCB, realizing a packaging compatible low-profile architecture with the total device area of 33 mm 2 . The measured isolation (IS) and insertion loss (IL) of the fabricated circulator at 35 GHz is 3.9 and 8.7 dB, respectively.
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Date Submitted: 9/13/22 12:00AM Date Published: 10/1/21 4:00AM
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Article Title: Screen-Printable, Self-Biased SrM/PDMS Composites for Integrated Magnetic Microwave Devices
Authors: Connor S. Smith, Renuka Bowrothu, Yuzheng Wang, Florian Herrault, Y. K. Yoon, David P. Arnold
Keywords: Magnetic materials, screen printing, self-biased magnetic
Abstract: This work introduces a material and method for high-volume, low-temperature, screen printing of self-biased magnetic films made from a composite of M-type strontium ferrite SrFe12O19 (SrM) particles and polydimethylsiloxane (PDMS). The magnetic particles are aligned under a dc magnetic field, while the PDMS is cured at 75 ?C, making this fabrication process compatible with semiconductor and printed-circuit-board substrates. Aligned composites with estimated SrM particle volume percentages of 14 vol.%, 20 vol.%, and 27 vol.% are fabricated, as well as an unaligned 14 vol.% composite for comparison. X-ray diffraction (XRD) and scanning electron microscopy (SEM) are used to examine the structure and composition of the composites. Furthermore, vibrating sample magnetometer and ferromagnetic resonance (FMR) measurements are performed to determine their dc and ac magnetic properties. Results show that the aligned composites have magnetic textures between 1.47 and 1.95, crystalline anisotropi
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CONFERENCE PAPERS:

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Conference Location: Hilton Head, SC
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Authors: Y. Wang, J. Ewing, and D. P. Arnold
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
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Conference Location: Ann Arbor, MI
Paper Title: Low-temperature micropatterning of thick-film BaFe12O19 composites on semiconductor substrates for integrated millimeter wave devices
Authors: C. Velez, J. Ewing, S. Hwangbo, K. Sondhi, T. Schumann, Y. K. Yoon, and D. P. Arnold
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Conference Location: Vancouver, Canada
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Authors: Yuzheng Wang, Beatriz Y. Jimenez and David P. Arnold
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Conference Location: Atlanta, GA, USA
Paper Title: Batch-fabricated substrate-embedded Ka-band self-biased circulators using screen-printed strontium hexaferrite/PDMS composite
Authors: R. Bowrothu, H. Kim, C.S. Smith, X.N. Guan, S. Cui, F. Herrault, D.P. Arnold and Y.K. Yoon
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Conference Location: Singapore, Singapore
Paper Title: Magnetically Tunable 28 GHz Array Antenna Using BaM/PDMS Composite
Authors: R. Bowrothu, H. Kim, C. Smith, D. Arnold, Y.K. Yoon
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Paper Title: Demonstration of Substrate-Embedded Nonreciprocal Millimeter-Wave Circulators For System-In-Packaging
Authors: Hae-In Kim, Renuka Bowrothu, Woosol Lee, Connor Smith, Leili Hayati, David P. Arnold, Yong-Kyu Yoo
Acknowledged Federal Support: **Y**

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Authors: Renuka Bowrothu
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Publication Type: Thesis or Dissertation
Institution: University of Florida
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Title: Magnetic 0-3 Nanocomposites for Power, Stretchable/Flexible, and Radio-Frequency Applications
Authors: Connor S. Smith
Acknowledged Federal Support: **Y**

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Title: Development of Ultrathick Electroplated CoPt Magnets and their Application in Electro-Permanent Magnet Device
Authors: Yuzheng Wang
Acknowledged Federal Support: **Y**

Partners

,

I certify that the information in the report is complete and accurate:
Signature: David P Arnold
Signature Date: 9/13/22 2:28PM

FINAL REPORT

ARO Grant Number: W911NF-17-1-0050

DARPA/MTO Program: Magnetic Miniaturized and Monolithically Integrated Components (M3IC)

Title: Magnetic Thick Films for Integrated Microwave Devices

Feb. 1, 2017 – May 15, 2022

Submitted by:
University of Florida
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I. Executive Summary

Program Overview

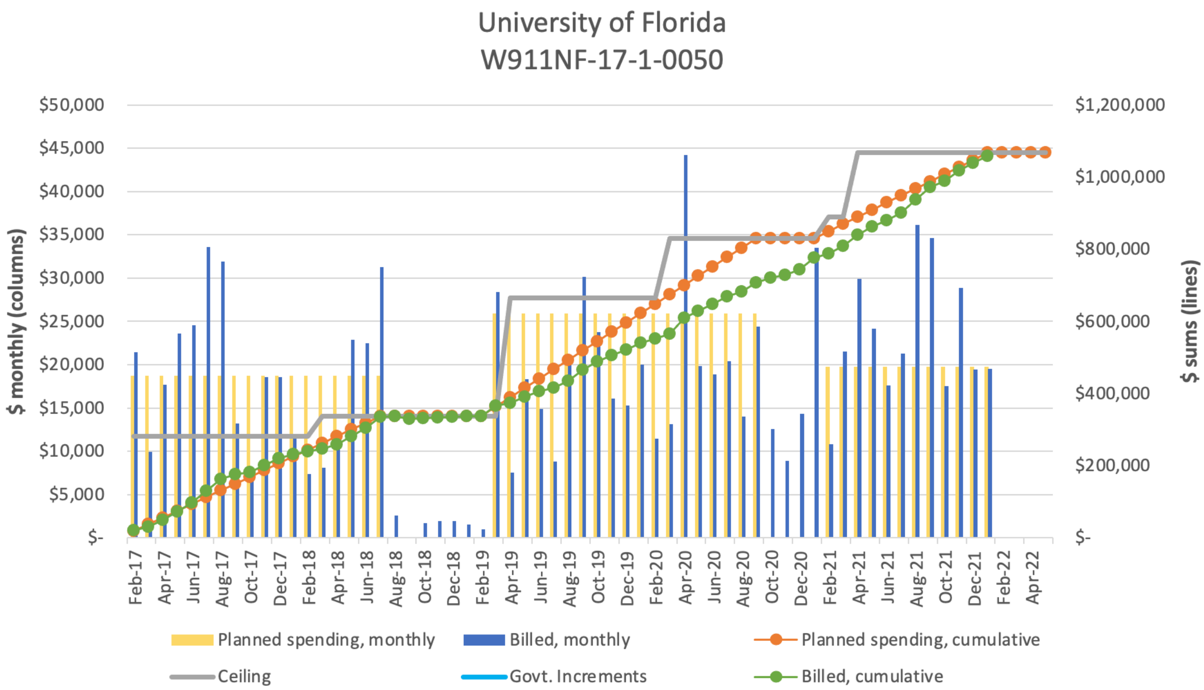
The University of Florida was awarded a grant (administered by Army Research Office) funded over three phases in response to a proposal submitted to the DARPA/MTO Magnetic Miniaturized and Monolithically Integrated Components (M3IC) program in *Technical Area 1A: Integration.* The work plan was organized in three thrusts: (1) **self-biased microwave ferrite thick-films** on semiconductor substrates, (2) integration of **permanent magnet bias magnets** on semiconductor substrates, and (3) **integrated microwave magnetic components** on semiconductor substrates. The key innovations include:

1. Development of magnetic thick-film deposition methods (solution-based direct-write "printing" methods and/or directed assembly) from hexaferrite nanoparticle precursors, which offer potential for rapid, large-area fabrication, lower-temperature processing, as well as high-performance microwave/mm-wave magnetic properties
2. Advancement of high-energy-density, high-remanence, process-integrable permanent micromagnets to replace bulky external bias magnets with compact on-chip integrated bias magnets thereby facilitating integrated microwave components using a wide variety of magnetic materials (under bias) and traditional film deposition methods
3. Demonstration of high-performance, fully microfabricated microstrip-fed circulator components integrated on semiconductor substrates with operating frequencies ranging from 1–110 GHz to showcase drastically improved SWAP compared to off-chip magnetic components.

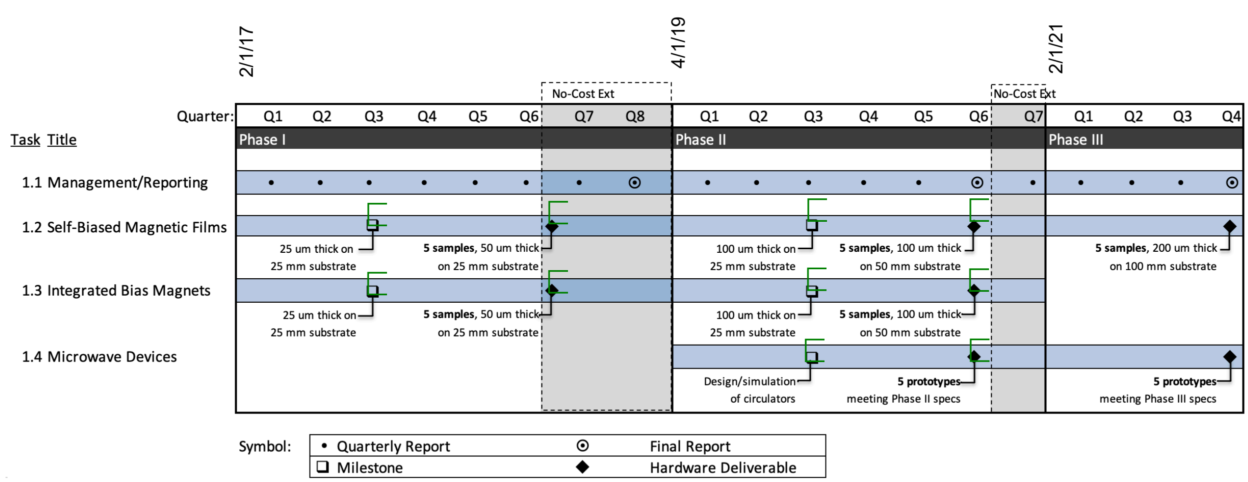
Table 1. Technology thrust areas.

Technology Thrust	Benefit/Impact
Thrust 1: Fabrication methods for integrating **lithographically patterned, self-biased magnetic thick-films** on semiconductor substrates from **nanoparticle precursors**	Eliminate the need for bulky external bias magnets, and thereby enable integration of magnetic components with semiconductor circuits
Thrust 2: Fabrication methods for electroplating **permanent bias magnets** on semiconductor substrates	Replace bulky external bias magnets with integrated on-chip bias micromagnets, and thereby enable integrated magnetic components using traditional microwave materials and more common film deposition techniques
Thrust 3: Demonstration of high-performance **microwave and mm-wave magnetic components** integrated on semiconductor substrates	Showcase the integrated magnetic technology and the opportunities for dramatic improvement in SWAP for end systems.

Financial Summary



Program Workplan and Deliverables



II. Summary of Technical Accomplishments

Below is a summary of key technical accomplishments. Extensive additional detail can be found in the previously submitted quarterly technical progress reports.

Thrust 1: Self-Biased Microwave Materials from Nanoparticle Precursors

The objective of this thrust is to develop new fabrication approaches for realizing ultra-thick (up to 200 μm), high-performance, patterned hexaferrite films on semiconductor substrates.

- Fabricated barium ferrite magnetic films with thicknesses up to 60 μm using nanoparticle precursors ranging from 15-90 nm in diameter.
- Investigated the annealing conditions to densify magnetic films and confirmed $BaFe_{12}O_{19}$ crystal structure in the sample annealed at 900 °C for 2 hr.
- Confirmed that sapphire serves as a diffusion-free substrate material for barium ferrite annealing, while silicon and quartz substrates show diffusion with barium ferrite at high temperatures.
- Demonstrated 1-μm-thick sputtered alumina (Al_2O_3) film as a suitable diffusion barrier layer on Si substrate for annealing barium ferrite particles at 1100 °C.
- Demonstrated magnetic anisotropy in barium ferrite films by evaporative deposition of barium ferrite nanoparticles in a bias dc magnetic field.
- Evaluated three fabrication process for hexaferrite nanocomposites (tape, screen printing, lithography) to integrate in in semiconductor process, yielding patterned structures with mm-feature sizes and thicknesses >130 μm and coercivities >250 kA/m.
- Simulated, fabricated, and tested co-planar waveguide (CPW) transmission line test jigs to facilitate material measurements from 30 GHz to 100 GHz, with dc bias magnetic fields up to 230 mT.
- Laser machined bulk barium hexaferrite (from Metamagnetics) down to a small (1 mm^3) test sample for RF characterization.
- Completed material and magnetic characterization of barium hexaferrite particles from three commercial vendors: Nanostructured Amorphous Materials, Alfa Aesar, and Sigma Aldrich.
- Completed RF measurements of 150-μm-thick barium hexaferrite material deposited on CPW transmission line. Measured zero field resonance (ZFR) at 47.76 GHz, with linear tunability of 12.7 GHz/T in response to bias field. Experimentally demonstrated a shift of 2.9 GHz (6% tunability) with bias fields up to +/-0.15 T.
- Demonstrated large-area barium hexaferrite composite films with dimensions up to 25 mm x 25 mm.
- Demonstrated barium hexaferrite composite material can be peeled, transfer or directly patterned in different substrates including glass (because curing temperature is only 70ºC). Moreover, the material is flexible enabling the potential integration of this composite in flexible/stretchable electronics.

- Proposed and proved a hypothesis that the FMR response may be “engineered” by forming composites comprising barium hexaferrite particles with other ferromagnetic particles (e.g. SmCo particles to add additional “internal bias”). The zero-bias FMR is shown to be tunable over a range of ~12 GHz (from ~41 GHz to 53 GHz) by controlling the relative ration of the BaM and SmCo particles, and 20% reduction (improvement) in the S21 bandwidth can be obtained.
- *Submitted BaM/PDMS samples as Phase I deliverables to NIST and NRL.*
- Successfully fabricated and characterized screen printed films with SrM particles provided from HRL
- Developed multiple techniques for increasing the anisotropy and squareness of the screen-printed films
- Fabricated and characterized films using BaM mixed with SmCo at various weight ratios. Collected SEM images of cross-sectioned BaM samples with different weight percentages of SmCo inclusions added showing distribution of particles. Measured the FMR of mixed ferrite films (BaM with SmCo inclusions) showing systematic trends in FMR frequency and linewidth based on inclusion type and ratio
- Began utilizing a shorted rectangular waveguide method (in additional to CPW test jig) for measuring the FMR of magnetic samples. Using the shorted rectangular waveguide method, measured a zero-field FMR of ~46 GHz for our BaM/PDMS material, matching the FMR value measured by NIST.
- Imaged the cross-sections of the commercial BaM particles and HRL particles (Batches 2, 3, and 4) to determine the change in alignment between aligned and un-aligned samples, but was unable to discern a difference using this imaging method.
- Validated a potting epoxy as an improved binder for screen-printable magnetic particle films (as opposed to PDMS)
- Received and measured FMR and hysteresis curves of 5 batches of SrM particles from HRL; Batch 4 shows a squareness of 0.82, magnetic texture of 0.22, and FMR frequency of 43.1 GHz
- *Submitted SrM/PDMS composite samples as Phase II deliverables to NIST and NRL.*
- Achieved a highly textured (magnetic texture of 3.14 vs. previous best of 1.95) for SrM composite made by aligning particles in low-viscosity isopropanol and then subsequently binding with vapor-deposited parylene coating.
- Unfortunately there was no significant improvement in FMR linewidth of the highly textured composites as compared to previously made SrM/PDMS composites samples.

Thrust 2: Integrated Bias (Permanent) Magnets

The focus of this trust is to develop thick-film (up to 200 μm) CoPt and FePt micromagnets on semiconductor substrates to serve as high-performance bias magnets for integrated magnetic components.

- Conducted longitudinal study of CoPt bath chemistry to examine how bath composition (e.g. metal ion concentrations, trace elements, contaminants) evolves with time (both shelf life and with usage).
- Evaluated various seed-layer metallurgies on silicon and sapphire substrates to maximize magnetic properties and substrate adhesion.
- Purchased and developed a 120-μm-thick dry film laminated photoresist process (WBR2120 from DuPont) to allow for thicker CoPt films to be plated.
- Demonstrated pulse-plating processes as effective in reducing cracks and possibly relieving the internal stress of electroplated CoPt films.
- Developed high-temperature and high-current-density electroplating processes that increased deposition rates by a factor of 10. Systematically studied high-temperature and high-current-density CoPt electroplating processes
- Demonstrated sputtered alumina electroplating masking layers, providing good adhesion on metal seed layers in heated bath under high current density (where photoresist molds have failed).
- Investigated current densities exceeding 1 A/cm^2, successfully electroplating numerous CoPt films, 40 – 60 μm with coercivities up to 850 kA/m and energy products up to 60 kJ/m^3.
- Demonstrated mechanical polishing process that reduced surface roughness of electroplated samples significantly.
- Optimized electroplating conditions for CoPt magnets and consistently achieved coercivity of 820 kA/m, thickness over 50 μm at moderate current density of 400 mA/cm^2.
- Conducted TEM/STEM characterization revealing, for the first time, the porous microstructure and average grain size of ~20 nm in annealed CoPt magnets, which matches XRD measurements.
- Performed XRD characterization on fabricated CoPt thick film magnets to confirm the phase transformation to L10 phase during thermal annealing and obtain the crystal information including lattice ratio c/a=0.94, L_{10} volume fraction of 62%, and an ordering parameter of 0.42.
- Explored magnetic field annealed CoPt magnets (magnetic field applied during annealing), but were unable to achieve any observable magnetic anisotropy.
- Developed an FePt electroplating process, studied the impact of electroplating variables to the magnetic performance of FePt magnets, yielding magnets with 900 kA/m coercivity (10% higher than the CoPt), remanence up to 0.61 T, and energy products up to 51.8 kJ/m3.
- *Submitted electroplated CoPt samples as Phase I deliverables to NRL.*
- Developed the coating and releasing process of >100 μm thick SU-8 electroplating molds
- Systematically studied the impact of bath temperature to the deposition rate and magnetic properties of deposited films.

- Explored the use of glycine as an additive to CoPt electroplating and its influence on the morphology and magnetic properties of deposited films.
- Scaled up the CoPt electroplating process 50 mm substrates and successfully deposited multiple 100 µm-thick films simultaneously using SU-8 molds.
- Confirmed the improvement in adhesion of thick CoPt films to silicon wafers using thermal oxide interface layer.
- Explored pulsed electroplating techniques for the thick CoPt deposition aiming for low-stress films and reduced surface roughness.
- Demonstrated CoPt electroplating process on full 4-inch silicon wafers (100 mm substrates).
- *Submitted electroplated CoPt samples as Phase II deliverables to NRL.*

Thrust 3: Integrated Magnetic Components

The objective of this thrust is to design, microfabricate, and test non-reciprocal circulator devices as test vehicles for highlighting the feasibility of integrated magnetic microwave and mm-wave component technologies.

- Successfully designed and simulated a circulator for operation at 28 GHz in HFSS, which can be flexibly redesigned to other frequencies.
- Developed process flow and fabricated round-1 BaM circulators using PCB manufacturing techniques and the BaM/PDMS composite material.
- Experimentally inferred/extracted the effective permittivity of PDMS/BaM composite, which was previously an unknown parameter, but critical for ongoing simulation/design
- Designed, fabricated, and tested BaM circulators targeting 35 GHz operation frequency with good match between simulation and measured results (isolation and insertion loss). Demonstrated 3.9 dB isolation with 8.7 dB insertion loss at 35.2 GHz. Using additional "helper" bias magnets, demonstrated an improved 7.4 dB isolation with 8.4 dB insertion loss at 35.4 GHz.
- Fabricated and tested round-3 BaM circulator devices yielding 2.7 dB isolation and an improved 5.8 dB minimum insertion loss at 37 GHz.
- Designed, fabricated, and tested round-1 SrM circulators (using HRL-provided SrM particles) targeting 35 GHz as operation frequency, confirming improved isolation compared to the BaM material. Demonstrated maximum isolation of 18.3 dB with minimum insertion loss of 6.6 dB.
- Fabricated and tested round-2 SrM circulators yielding nearly 15 dB isolation with an improved 4.9 dB minimum insertion loss at 37 GHz.
- Simulated preliminary designs of tunable notch filters, yielding 3.7 GHz / kOe tunability at nominal operating frequency of 44 GHz
- Redesigned and simulated round-3 SrM circulators with orthogonal T-shaped feed lines,

and fine-tuned the fabrication process to reduce device insertion losses.

- Fabricated and tested round-3 SrM circulators with orthogonal T-shape feed lines yielding isolation of 10.1 dB with insertion loss of 4.2 dB at 35GHz (matches simulation well).
- Performed high power handling measurement on SrM HRL circulators, demonstrating linear response up to +35 dBm (=3.16 W) (limited by test setup).
- Designed, fabricated and characterized a magnetically tunable 2x2 array antenna operating at 28 GHz with a tunability of 0.3 GHz.
- Simulated preliminary designs of tunable notch filter based on Sr/PDMS, yielding 1.4 GHz/T tunability at nominal operating frequency of 34.8 GHz.
- Fabricated tunable notch filter based on SrM/PDMS.

III. Products

Journal Publications (5)

1. Y. Wang, J. Ewing, and D. P. Arnold, "Ultra-thick electroplated CoPt magnets for MEMS," *J. Microelectromech. Syst*., vol. 28, no. 2, pp. 311-320, Apr. 2019.
2. C. Velez, S. Hwangbo, S. Chyczewski, J. Ewing, R. Bowrothu, C. Smith, Y.-K. Yoon, and D. P. Arnold, "Investigation of ferromagnetic resonance shift in screen-printed barium ferrite/samarium cobalt composites," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 8, pp. 3230-3236, Aug. 2019.
3. Y. Wang, R. Bowrothu, Y.-K. Yoon, and D. P. Arnold, "Patterning of thick electroplated CoPt magnets using SU-8 micromoulds," *Micro Nano Lett*., vol. 14, no. 14, pp. 1393-1396, Dec. 2019.
4. R. Bowrothu, H. Kim, C. S. Smith, D. P. Arnold, and Y. K. Yoon, "35-GHz barium hexaferrite/PDMS composite-based millimeter-wave circulators for 5G applications," *IEEE Trans. Microw. Theory Techn*., vol. 68, no. 12, pp. 5065-5071, Dec. 2020.
5. C. S. Smith, R. Bowrothu, Y. Wang, F. Herrault, Y. K. Yoon, and D. P. Arnold, "Screen-printable, self-biased SrM/PDMS composites for integrated magnetic microwave devices," *IEEE Trans. Magn*., vol. 57, no. 10, 2800905, 5 pages, Oct. 2021.

Conference Publications (6)

1. Y. Wang, J. Ewing, and D. P. Arnold, "Increasing the thickness and deposition rate of high-performance electroplated CoPt permanent magnets," *Tech. Dig. Solid-State Sensors, Actuators, and Microsystems Workshop*, Hilton Head, SC, June 2018, pp. 136-139.
2. C. Velez, J. Ewing, S. Hwangbo, K. Sondhi, T. Schumann, Y. K. Yoon, and D. P. Arnold, "Low-temperature micropatterning of thick-film $BaFe_{12}O_{19}$ composites on semiconductor substrates for integrated millimeter wave devices," *Proc. IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes 2018* (IMWS-AMP 2018), Ann Arbor, MI, July 2018.
3. Y. Wang, B. Y. Jimenez, and D. P. Arnold, "100-um-thick high-energy-density electroplated CoPt permanent magnets," *Proc. 33rd IEEE Intl. Conf. Micro Electro Mechanical Systems* (MEMS 2020), Vancouver, Canada, Jan. 2020, pp. 558-561.
4. R. Bowrothu, H. Kim, C.S. Smith, X.N. Guan, S. Cui, F. Herrault, D.P. Arnold and Y.K. Yoon, "Batch-fabricated substrate-embedded Ka-band self-biased circulators using screen-printed strontium hexaferrite/PDMS composite" *Proc. 2021 IEEE MTT-S International Microwave Symposium (IMS)*, Atlanta, GA, June 2021, pp. 323-326.
5. R. Bowrothu, H. Kim, C. Smith, D. Arnold, Y.K. Yoon, "Magnetically tunable 28 GHz array antenna using BaM/PDMS composite," *Proc. 2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Singapore, Dec. 2021, pp. 1393-1394.
6. H. Kim, R. Bowrothu, W. Lee, C. Smith, L. Hayati, D. P. Arnold, and Y.-K. Yoon, "Demonstration of substrate-embedded nonreciprocal millimeter-wave circulators for

system-in-packaging" *Proc. 35th IEEE Intl. Conf. Micro Electro Mechanical Systems* (*MEMS 2022*), Tokyo, Japan, Jan. 2022, pp. 1034-1037.

Conference Presentations (9)

1. X. Wen, Y. Wang, S. Hwangbo, Y.-K. Yoon, and D. P. Arnold, "Thick-film magnetic materials for integrated microwave systems," presented at *Napa Microsystems Workshop*, Napa, CA, Aug. 2017. (oral)

2. J. Ewing, Y. Wang, D. P. Arnold, "Stress control in thick CoPt magnetic films through pulsed electrodeposition," presented at *62nd Annual Magnetism & Magnetic Materials (MMM) Conf.*, Pittsburg, PA, Nov. 2017. (oral)

3. Y. Wang, J. Ewing, and D. P. Arnold, "Increasing the thickness and deposition rate of high-performance electroplated CoPt permanent magnets," presented at *Solid-State Sensors, Actuators, and Microsystems Workshop*, Hilton Head, SC, June 2018. (poster)

4. Y. Wang and David P. Arnold, "Development of electroplated FePt thick films on silicon wafers" presented at *Intl. Conf. Magnetism 2018*, San Francisco, CA, July 2018. (poster)

5. C. Velez, J. Ewing, S. Hwangbo, K. Sondhi, T. Schumann, Y. K. Yoon, and D. P. Arnold, "Low-temperature micropatterning of thick-film BaFe12O19 composites on semiconductor substrates for integrated millimeter wave devices," presented at *IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes 2018* (IMWS-AMP 2018), Ann Arbor, MI, July 2018. (oral)

6. Y. Wang, B. Y. Jimenez, and D. P. Arnold, "100-um-thick high-energy-density electroplated CoPt permanent magnets," presented at *IEEE Intl. Conf. Micro Electro Mechanical Systems* (MEMS 2020), Vancouver, Canada, Jan. 2020. (poster)

7. R. Bowrothu, H. Kim, C.S. Smith, X.N. Guan, S. Cui, F. Herrault, D.P. Arnold and Y.K. Yoon, "Batch-Fabricated Substrate-Embedded Ka-Band Self-Biased Circulators Using Screen-Printed Strontium Hexaferrite/PDMS Composite" presented at *2021 IEEE International Microwave Symposium (IMS)*, Atlanta, GA, June 2021. (oral)

8. R. Bowrothu, H. Kim, C. Smith, D. Arnold, Y.K. Yoon, "Magnetically Tunable 28 GHz Array Antenna Using BaM/PDMS Composite," presented at *2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Singapore, Dec. 2021. (oral)

9. H. Kim, R. Bowrothu, W. Lee, C. Smith, L. Hayati, D. P. Arnold, and Y.-K. Yoon, "Demonstration of substrate-embedded nonreciprocal millimeter-wave circulators for system-in-packaging" presented at *35th IEEE Intl. Conf. Micro Electro Mechanical Systems* (*MEMS 2022*), Tokyo, Japan, Jan. 2022. (poster)

Dissertations (3)

1. Renuka Bowrothu, "Energy Efficient Passives for 5G and Millimeter Wave Applications," Ph.D. Dissertation, University of Florida, May 2021.

2. Connor Smith, "Magnetic 0-3 Nanocomposites for Power, Stretchable/Flexible, and Radio-Frequency Applications," Ph.D. Dissertation, University of Florida, Aug. 2021.

3. Yuzheng Wang, "Development of Ultrathick Electroplated CoPt Magnets and their Application in Electro-Permanent Magnet Device," Ph.D. Dissertation, University of Florida, Aug. 2021.

Tech Transfer

Nothing to report.