Executive Summary

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1. **Title of the Project:** Development of integrated miniature magnet free microwave circulator

2. **Date of Start of the Project:** October 1, 2021

3. **Aims and Objectives:** To develop miniaturized magnet free microwave circulators using ferroelectric thin film based varactors and resonators for facilitating non-reciprocal applications. This product technology development is required for next generation mobile communication and quantum computing.

4. **Significant achievements (not more than 500 words to include List of patents, publications, prototype, deployment etc)**

- An MIC based prototype was designed, simulated, fabricated with imported discrete components and tested. It worked and showed that the concept is working. Therefore the integrated design and fabrication effort could be launched with confidence. Simulation of the equivalent circuit of resonator and varactor are done using Advanced Design System (ADS) and the simulation of the proposed design at 2.5 GHz frequency for magnet less circulators using narrow band devices done and results are reported. The varactor fabrication with and without a floating metal design is achieved. For the resonator fabrication, wet chemical etching of the silicon nitride layer is done. The etch rate achieved for the silicon nitride film with the mixture of 6 ml of HF + 40g NH_4F powder to 60 ml of DI water at temperature of 80^0C and etch rate achieved is around 20 nm/minute. Silicon wet chemical etching to fabricate the resonators is done using

KOH solution (125 gm of KOH + 500 ml of Deionized water) at 95^0C and etch rate achieved is 1.6 um/minute. We are able to etch up to 250 um thickness of silicon and the process development continues. To etch the $Ba_{0.5}Sr_{0.5}$ TiO_3 (BST) film, a wet chemical etching process will be used. The etch rate achieved for the BST film with the mixture of the HF: HNO_3:H_2O_2:H_2O in the ratio of 1:25:50:20 is around 35 nm/minute. BST based Metal Insulator Metal (MIM) varactor structure incorporating a coplanar waveguide (CPW) is fabricated. The operation of the proposed varactor is based on the field-dependent material properties of BST thin film. A capacitance tunability of 70% has been achieved for the bias voltage of 0–10 V over a frequency range of 1–10 GHz. The dimensions of FBAR and varactor structures are finalized. In design they are being integrated into the Wye configuration which is a difficult task. The corresponding layout pattern for proposed configuration is designed and is going to be simulated. Then the masks for it's fabrication will start. Once the masks are ready, the first round of fabrication could be commenced.

Provisional Indian Patent Granted:

1. Title: "FABRICATION OF MICROWAVE VARACTORS ON POLYMER SUBSTRATES USING LOW-TEMPERATURE CRYSTALLIZED FERROELECTRIC THIN FILMS"

Inventors/Authors: Akhil Raman T S, Chedurupalli Shivakumar, K.C. James Raju

Application Number: 202241032453, Application Date: 7-June-2022

Papers published in refereed Journals.

i. C. Thirmal, P. Nikhil Mohan, G. Suresh, K.C. James Raju, T. Vishwam, Improved dielectric and AC conductivity properties of P(VDF-TrFE)-Nafion blends for high-temperature flexible capacitor applications, Current Applied Physics,Volume 44 Pages 63-70,2022.

ii. J. Pundareekam Goud, Ajeet Kumar, Mahmoud S. Alkathy, Kongbrailatpam Sandeep, Akhil Raman TS, Bibhudatta Sahoo, Jungho Ryu, K.C. James Raju,"Thickness dependence of microwave dielectric tunability in Ba0·5Sr0·5TiO3 thin films deposited by pulsed laser deposition", Ceramics International,2022.

iii. Nair, V.R., Raman, T.S.A., Alkathy, M.S. *et al.* Effect of nickel and zinc co-substitution on the structural and dielectric properties of barium titanate ceramics. *J Mater Sci: Mater Electron* 33, 13814–13825 (2022). https://doi.org/10.1007/s10854-022-08313-7.

iv. Shivakumar Chedurupalli, T Vishwam and James Raju K.C, "Complex Permittivity Measurement of Liquids Using Half Mode Corrugated Substrate Integrated Waveguide Structure", 978-1-6654-0662-2022 IEEE 98th ARFTG Microwave Measurement Conference.

v. Shivakumar Chedurupalli, Karthik Reddy K, Akhil Raman T S and James Raju K.C, "High Overtone Bulk Acoustic Resonator with Improved effective Coupling coefficient ", IEEE International Symposium on Applications of Ferroelectrics (ISAF) 2022.

vi. Shivakumar Chedurupalli, , Bhanu Prakash S, Akhil Raman T S, Kanaka Ravi Kumar and James Raju K.C, "Porous silicon based bulk acoustic resonator using Barium Strontium Titanate thin film", IEEE International Symposium on Applications of Ferroelectrics (ISAF) 2022.

Concluding remarks

- Schematic simulation of the proposed magnet less circulator at 2.5 GHz is done in ADS software. The basic steps involved in the fabrication process like etching of silicon nitride layer of the SOI wafer and deposited BST film by wet chemical etching process have progressed. To fabricate the FBAR resonator, initial trials with deep back side etching of silicon substrate is progressing with wet chemical etching. Dry etching method would be attempted as it is a superior process, once the system is completed to handle the required process gasses. Layout of FBAR resonator and varactor are finalized, while the design of the non magnetic circulator is being carried out. Once the design is simulated, the masks would be prepared so that it could be fabricated.

Report of the visit made with funds available by the fellowship:

1. Attended and presented an Invited Talk at 2022 International Workshop on Thin films for Electronics, Electro-optics, Energy and Sensors (TFE3S) to be held at the Northeastern University, Boston, MA, August 10-12, 2022.

2. Spent time in the lab of Prof. Nian X Sun of Northeastern University, Boston, USA during August 7 to 19 as a Visiting Scientist and established technical collaborations.

3. Visited Prof.Caroline Ross of MIT, Boston, USA and established technical collaborations.

With Prof.Nian X Sun at Northeastern University, Boston, USA