Nanotechnology-Inspired Multi-Layer Conductors for High Performance Microwave Passive Components

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***Abstract*—In this report, a summary of research results and potential applications are provided on multi-layer conductors consisting of alternating nano-superlattice structures for use in microwave passive components. The proposed meta-conductors are engineered to have properties in microwave that cannot be readily found in intrinsic materials in nature. Especially, investigated are ferromagnetic materials that have extremely dynamic frequency-dependent properties in frequencies ranging from DC to K-band (18–26 GHz) such as Ni and NiFe. As results of this research, conductors with reduced ohmic resistance in K-band are realized and low loss transmission lines are demonstrated. Also, the proposed conductor architecture has been utilized in conjunction with a low loss glass interposer technology so that RF passives with improved microwave performance are presented. As a new application to the multi-layer conductors, a tunable conductor, the so-called magnetic field effect transconductor (M-FET) with tunable ohmic resistance is presented with 700% frequency tunability at 600 Oe DC magnetic field.**

***Index Terms*—Ferromagnetic materials, high-Q RF passives, nano-superlattice conductors, magnetically tunable conductors.**

I. Introduction

A New class of conductors are introduced which are specifically engineered to have dynamic properties in the microwave regime. As the operating frequency of circuits and systems increases, the current is confined to the outmost area of the conductor based on the skin effect theory, which results in the increase of radio frequency resistance. The current profile can be altered by employing multiple nanoscale heterogeneous layers. In this study, ferromagnetic materials are combined with regular conductors to form nanotechnology-inspired multi-layer conductors, the so-called meta-conductors, with useful RF properties such as low RF resistance and magnetic tunability that are discussed in the remaining of this report.

II. Conductor Architectures for RF Loss Reduction

The electrical conductivity of the transmission lines and RF passive components is limited by the inherent material resistance and the internally induced loss mechanism dominated by the skin effect which causes the RF resistance to continuously grow as the frequency increases ultimately degrading the performance of overall RF systems [1]. In this work, the RF ohmic loss reduction is achieved with a non-ferromagnetic conductor such as copper accompanied in close proximity by a ferromagnetic material such as Ni and NiFe with negative magnetic permeability in the frequency of interest. The negative permeability ferromagnetic material will produce eddy currents in an opposite direction of those of copper with positive magnetic permeability, canceling out both eddy currents from the two neighboring conductors, the so called eddy current cancelling effect (ECC) [2]. Fig. 1 (a) shows the ECC effect of the proposed multi-layer conductors with their current distribution. While the current amplitude drops exponentially through the volume of a solid conductor, where the thickness of the non-ferromagnetic conductor is greater than the skin depth at a given frequency, the current amplitude will be uniformly distributed in the superlattice conductor with thin Cu/NiFe layers, resulting in an increased effective skin depth and therefore lowered ohmic resistance. Fig. 1 (b) and (c) show the micrographs of the fabricated inductors and transmission lines as well as the cross section view of the multi-layer nano-superlattice conductors. More than 50% ohmic resistance reduction is achieved at the ECC frequency of 18-20 GHz using 10 pairs of Cu/NiFe conductors with a thickness of each Cu and NiFe layer of 150 nm and 30 nm, respectively (Fig. 1. (d)).

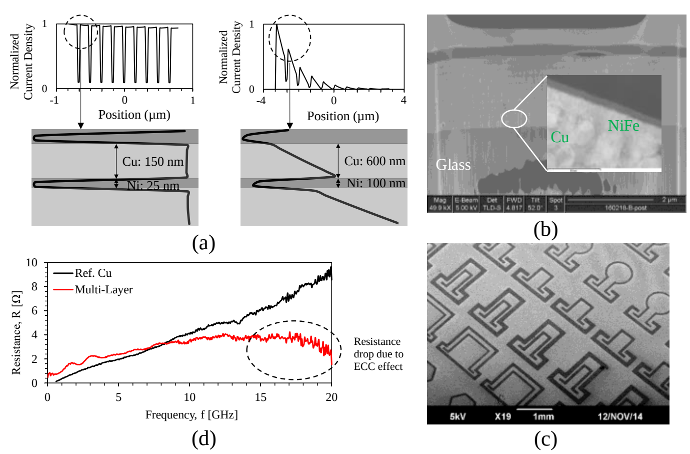

Fig. 1. (a) The current distribution into the volume of the conductors with the ECC effect, (b) the cross section view of the fabricated superlattice conductors, (c) the top view micrograph of the inductors, and (d) the measured ohmic resistance of transmission lines made of reference solid Cu and 10 paired Cu/NiFe with the same total thicknesses.

Although the conductor loss reduction is experimentally demonstrated and optimized for a single transmission line using multi-layer conductors, the research is further extended to utilize the proposed conductor architecture to improve the performance of other microwave and mm-wave passive components. For the first time, we report on in-substrate passive components using a high performance glass interposer and through glass via (TGV) technology and a multi-layer superlattice conductor architecture. Greatly reduced RF loss is achieved using the combination of the low dielectric loss glass substrates and the superlattice conductors. Half mode substrate integrated waveguide (HMSIW) resonators and two-pole bandpass filters, embedded inside a glass interposer substrate, are used as test vehicles for the demonstration of insertion loss improvement in K-band. The utilized conductor is made of 10 pairs of Cu/NiFe layers with each pair of 360 nm/30 nm, respectively. Fig. 2 shows the measurement results of the implemented resonator with a center frequency of 18 GHz for the multi-layer conductor and the solid Cu conductor as reference. The devices made of the Cu/NiFe and solid Cu conductors feature an insertion loss of 0.51 dB and 0.73 dB at 18 GHz, respectively, showing a significant loss reduction of 0.22 dB for the Cu/NiFe superlattice conductor as shown in Fig. 2 (b).

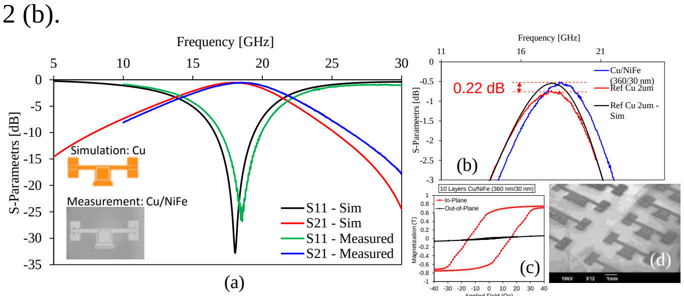

Fig. 2. (a) The comparison of the simulation and measurement results of the designed resonator. The measurement results are performed for the devices using nano-machined Cu/NiFe conductors while the simulations utilize a reference solid copper conductor, (b) the zoomed-in version of the insertion loss of (a) where comparison of the measurement results of the devices made of Cu/NiFe and solid copper conductors is given, (c) magnetic characterizaion results, and (d) the SEM micrographs of the implimented passives.

III. Magnetic Field Effect Transconductors

In this section, an electrical conductor with a magnetic field dependent conductance change is presented, where the conductor consists of multiple pairs of nanoscopic non-ferromagnetic Cu and ferromagnetic $Ni_{80}Fe_{20}$ metals [3]. The electrical conductance also shows its dependence on the thickness ratio of Cu and $Ni_{80}Fe_{20}$ layers. Upon applying an external DC magnetic field in the same direction with the electromagnetic (EM) wave propagation direction in a coplanar waveguide (CPW), the magnetic moment of $Ni_{80}Fe_{20}$ is aligned with the magnetic field direction of the EM wave, causing the EM energy to be transferred to the spin torque and dissipated as heat, resulting in the decrease of electrical conductance. With a magnetic field of 0 and 600 Oe, the ferromagnetic resonance frequency changes from 900 MHz to 7 GHz (more than 700 % frequency tunability) and so is the maximum electrical resistance point.

Fig. 3. (a) and (b) show the operating theory of the proposed magnetic field transconductor (M-FET). Since both Cu and $Ni_{80}Fe_{20}$ layers are selected a few times thinner than the skin depth of current in frequencies close to ferromagnetic resonance (f_{FMR}), the $Ni_{80}Fe_{20}$ layers in proximity of the Cu layers will absorb the electromagnetic energy by spin torque energy transfer when the DC magnetic field is perpendicular to the AC magnetic field of the electromagnetic wave, resulting in the increased effective resistance of the total conductor. As the spin torque transfer mechanism occurs near the f_{FMR} frequency, the realized M-FET conductors will show a frequency-selective conductor behavior (Fig. 3 (b)). Also, the thickness ratio of the conductor architecture will behave like a doping effect in semiconductor theory and change the resistance of the conductor (Fig. 3 (e)).

The unique property of the proposed conductors to have a tunable ohmic resistance (biased by an external magnetic field) and also the dependence of the ohmic resistance of the line on the thickness of the ferromagnetic material will allow an analogy with a MOSFET transistor in linear region except that M-FET is made of pure conductors (Fig. 3 (f)). The applications of the proposed M-FET include tunable transmission lines, resonators, metamaterials, and microwave absorbers.

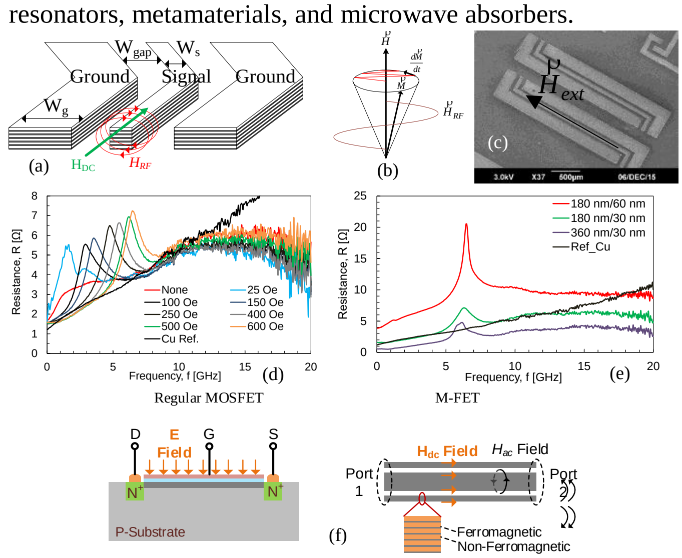

Fig. 3. (a) The proposed M-FET conductor architecture with AC and DC magnetic fields, (b) the demonstration of the precessing movement of the magnetic moment and magnetic spin torque transfer when RF magnetic field is perpendicular to the DC magnetic field at resonance, (c) the SEM image of an M-FET, (d) the ohmic resistance of the M-FET under different magnetic fields, (e) M-FET resistance dependence on the thickness of the NiFe layers, and (f) the schematics comparing the semiconductor-based MOSFET and the proposed conductor-based M-FET.

Arian Rahimi will pursue his future career as an R&D engineer in Intel Corporation, Portland, OR, USA. The fellowship from IEEE MTT society was a great motivation for him to further investigate his research. Attending IMS 2016 gave him the opportunity to talk to industrial partners that inspired him to apply his research outcomes and learnings in real life.

References

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