ADVANCING MILLIMETER-WAVE TECHNOLOGIES: HIGH-EFFICIENCY 3D AIR-LIFTED INDUCTORS FEATURING A HIGHLY MANUFACTURABLE CU/CO METACONDUCTOR

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ABSTRACT

This work introduces high-efficiency 3D air-lifted inductors designed for millimeter-wave applications utilizing a Cu/Co metaconductor. The metaconductor's superlattice structure, incorporating alternating layers of ferromagnetic (Co) and non-ferromagnetic (Cu) metals, significantly reduces conductor loss by mitigating the skin effect at targeted frequencies. A fabricated air-lifted metaconductor inductor exhibits a Q-factor of 49.4 at 31.8 GHz, demonstrating a 175% improvement compared to its solid Cu counterpart. Importantly, the employed fabrication process leverages cost-effective and scalable electrodeposition, overcoming limitations associated with traditional physical vapor deposition techniques. This electrodeposition process achieves a low surface roughness, with an average roughness (Ra) of 8.36 nm. This approach paves the way for the development of high-performance, manufacturable metaconductor-based devices for future RF systems operating at mmWave frequencies.

KEYWORDS

Air-lifted inductor; Cu/Co metaconductor; Skin effect; Electrodeposition; mmWave applications

INTRODUCTION

The advent of 5G and the imminent arrival of 6G technology underscore our unyielding quest for faster, more reliable communication systems. These advancements are propelled by the escalating demand for higher data transfer rates and the seamless connectivity needed for an expanding network of wireless devices. The key question is: Why do we move to higher operational frequencies?

5G and 6G technologies promise to redefine wireless communications, offering faster downloads, low latency, and unlocking the full potential of the Internet of Things (IoT). Their defining feature is the use of higher operational frequencies, providing a spectrum ripe for innovation.

Meanwhile, they also pose challenges. Notably, elevated losses due to the skin effect, which is the tendency of alternating current to concentrate near the surface of a conductor, can deteriorate the signal and power integrity of the entire system. Metaconductors, constructed from the superlattices of non-magnetic and ferromagnetic metals, emerge as a promising solution for mitigating the skin effect and reducing conductor losses in millimeter-wave applications, as depicted in Figure 1 [1, 2].

Yet, despite such potential, the current bottleneck in metaconductor technology is the manufacturing process, particularly physical vapor deposition (PVD) [3, 4], characterized by low accessibility, limited applicability, and high costs. To overcome scalability and cost challenges, there is a critical need for a highly manufacturable process. Electrodeposition offers scalability, cost-effectiveness, and compatibility with established MEMS and CMOS processes, and the effectiveness of the electrodeposition process for fabricating alternating superlattice devices has been demonstrated [5, 6]. However, the surface roughness of the fabricated device was micro-scale, and the fabrication process was not fully optimized for the smooth surface roughness.

To address these challenges, we implement metaconductors using an electrodeposition process in this research, which offers scalability, cost-effectiveness, and compatibility with existing MEMS and CMOS processes. Through experimentation and analysis, we demonstrate the efficacy of our electrodeposition process in fabricating alternating superlattice devices with a surface roughness of less than ten nanometers. Furthermore, we explore the performance and applicability of metaconductors in practical millimeter-wave applications, aiming to mitigate the skin effect and reduce conductor losses. Our findings lay the groundwork for the widespread adoption of metaconductors in next-generation wireless communication systems, enabling faster, more reliable, and energy-efficient operation in the era of 5G and beyond.

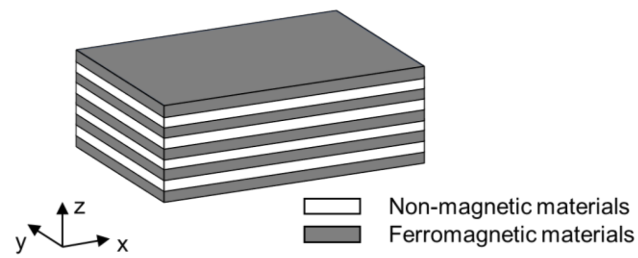

Figure 1: Schematic diagram of the metaconductor, comprising ferromagnetic and non-ferromagnetic metals in a superlattice structure.

THEORY

The skin effect poses a significant challenge for traditional conductors at high frequencies. As the alternating current tends to concentrate near the surface of the conductor, it increases conductor loss, leading to high heat generation. Metaconductors offer a promising solution to this issue. These engineered materials consist of a superlattice structure comprising alternating thin nano-layers of non-magnetic and ferromagnetic metals.

The relative magnetic permeability of the ferromagnetic film within the superlattice is a key determinant of metaconductor performance. It exhibits a complex dependency on material properties and frequency, with ferromagnetic resonance (FMR) and antiferromagnetic resonance (AFMR) frequencies playing crucial roles. In the critical frequency range between FMR and AFMR, the real part of the relative magnetic permeability becomes negative, effectively reducing the overall effective magnetic permeability within the metaconductor. This negative magnetic permeability interacts with the positive magnetic permeability of non-magnetic layers, leading to an increased skin depth and a more uniform distribution of current density across the conductor's cross-section. By mitigating the concentration of current near the surface, metaconductors alleviate conductor loss associated with the skin effect, resulting in significant improvements in power efficiency.

Achieving optimal performance requires careful design considerations, including optimizing the ferromagnetic material properties to achieve the desired negative magnetic permeability behavior at the target operational frequency and reducing the surface roughness of multilayered structures. Ultimately, metaconductors leverage their unique structure and negative magnetic permeability concept to manipulate electromagnetic wave behavior, offering a promising avenue for enhancing signal and power integrity in communication systems operating at high frequencies.

DESIGN AND FABRICATION

This section details the design and fabrication processes for the air-lifted Cu/Co metaconductor inductors.

Design

The high frequency structure simulator (HFSS, v. 15.0, ANSYS Inc.) was used to design and validate the RF performance of the 3D air-lifted Cu/Co metaconductor inductors. As shown in Figure 2, a one-port inductor structure was chosen with a 50 Ω matched coplanar waveguide (CPW) feed. The CPW feed has a gap of 29 µm, a signal line width of 175 µm, and a length of 300 µm. The ground planes have a width of 900 µm. In Figure 2, length L is defined as the distance between the ends of the bonding wire. The bonding wire itself has a diameter of 25 µm and is surrounded by the alternately deposited 10 pairs of Cu/Co metaconductor.

The simulation confirmed the expected behavior of the LC resonant frequency. For an inductor length (L) of 100 µm, the resonant frequency exceeded 50 GHz. This highlights the key role of inductance (L) in determining the resonant frequency. As the inductor length increases (L increases), the inductance also increases. According to the formula for LC resonance ($f = 1/(2\pi\sqrt{(LC)})$), a higher inductance value lowers the overall resonant frequency.

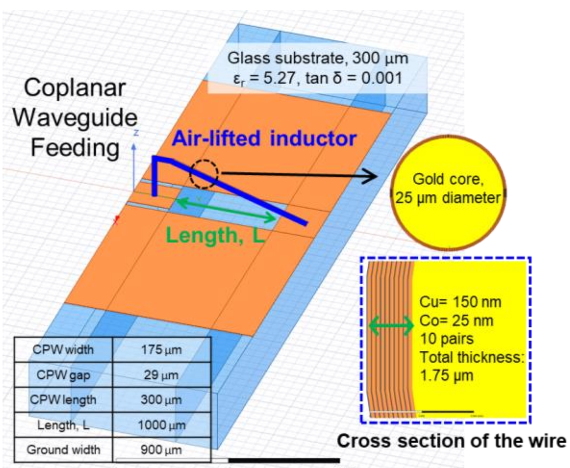

Figure 2: Schematic diagram of the designed air-lifted Cu/Co metaconductor inductor with a length (L) of 1000 µm, simulated in the High Frequency Structure Simulator (HFSS).

Fabrication

An experimental demonstration was conducted to validate the effectiveness of the air-lifted Cu/Co metaconductor inductors in suppressing the skin effect at the targeted frequencies. Figure 3 illustrates the detailed fabrication procedures for the air-lifted inductor, which consists of 10 pairs of Cu/Co deposited on a gold bonding wire using electroplating processes.

Initially, a smooth, low-loss glass substrate (EAGLE XG, Corning Inc.) with a dielectric constant (ε_r) of 5.27, a loss tangent (tan δ) of 0.001, and a thickness of 300 µm was prepared following piranha cleaning. Subsequently, a thin titanium (Ti) adhesion layer followed by a Cu seed layer was deposited using a multi-source DC/RF sputtering tool (CMS-18, Kurt J. Lesker Inc.).

The design of the CPW and air-lifted inductor was photo-patterned using a 4 µm thick negative photoresist (AZ® nLOF, Microchemicals GmbH). Electroplating was then used to deposit Ni/Au wire bonding seed layers. The Ni interlayer serves as a diffusion barrier between the Cu and Au layers, preventing Cu electromigration into the Au layer, which could lead to oxidation and degradation of RF performance. Without the Ni layer, it would be difficult to electroplate the Au layer directly onto the Cu.

A 1 mil diameter gold core wire was wire bonded onto the electroplated Au layer using a ball wire bonder (4124, Kulicke & Soffa Inc.) under controlled parameters including temperature (below 110 °C), applied force, power, and bonding time. Subsequently, 10 pairs of Cu/Co metals were deposited alternately using lab-made Cu and Co electroplating solutions [7]. Additives such as saccharin, polyethylene glycol, and sodium lauryl sulfate were included in the electrolyte to ensure a smooth surface for the electroplated metal thin films. Finally, an Au antioxidation layer (50 nm thick) was plated on the outermost layer of the Cu/Co superlattice. The Cu and Ti seed layers were then selectively wet-etched after removing the photoresist patterns to complete the fabrication process.

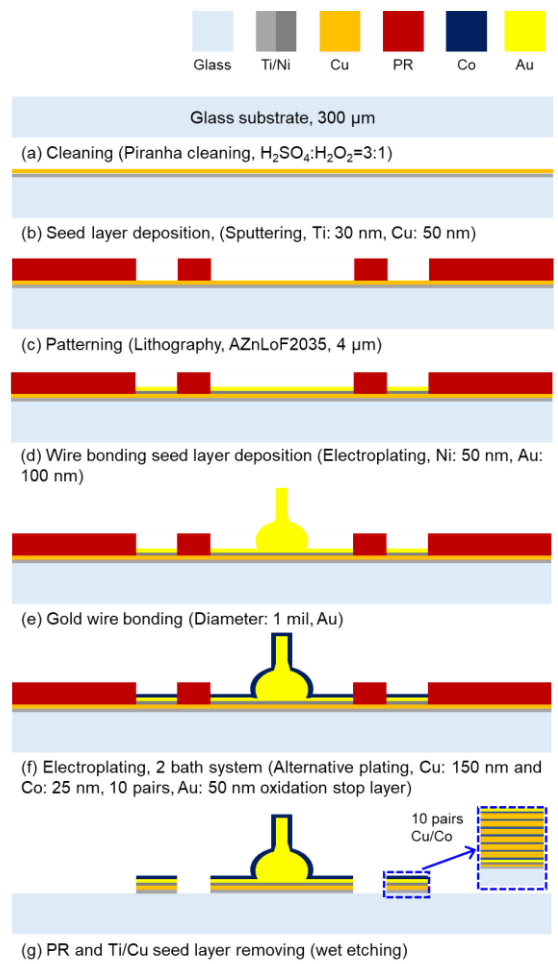

Figure 3: Schematic illustration of the fabrication process for air-lifted Cu/Co metaconductor inductors utilizing both wire bonding and electrodeposition processes.

MEASUREMENT RESULTS

Following the design and fabrication of the air-lifted Cu/Co metaconductor inductors, a comprehensive evaluation was conducted to assess their physical and electrical characteristics. This section delves into the measurement results, focusing on two key aspects: surface characterization and RF performance.

Surface Characterizations

A thorough examination of the air-lifted Cu/Co metaconductor inductors' surface morphology and topography was conducted using scanning electron microscopy (SEM) and an optical profilometer (Contour GT-I, Bruker). Analyzing these surface characteristics is crucial because they can significantly impact the inductors' electrical behavior at high frequencies.

Figure 4 presents SEM images of the fabricated inductors. Figure 4(a) shows multiple air-lifted Cu/Co metaconductor inductors with varying lengths, ranging from 200 μm to 400 μm. Figure 4(b) provides a high-magnification view of a single inductor's surface. To analyze the layering structure of the Cu/Co metaconductor in more detail, a cross-sectional SEM image is presented in Figure 4(c). This image reveals the arrangement of the alternatively deposited Cu/Co multilayers surrounding the bonding wire, with thicknesses of 208 nm and 41 nm for Cu and Co, respectively.

Complementing the cross-sectional analysis, Figure 5 describes the bonding wire structure after being plated with 10 pairs of Cu/Co following focused ion beam (FIB) milling. This measurement provides a highly detailed view of the interface between the Cu/Co metaconductor and the bonding wire, confirming uniform electrodeposition for 3D structures.

Figure 6 presents the surface profile of the CPW feeding line, obtained using an optical profilometer. The measurement yielded an average surface roughness (Ra) of 8.36 nm and a root mean square (RMS) surface roughness (Rq) of 11.16 nm. These low roughness values indicate a smooth surface profile, which is desirable for minimizing signal scattering and power losses in high-frequency applications.

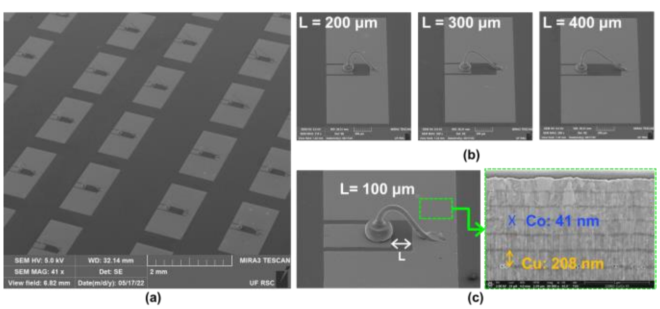

Figure 4: (a) SEM image of electrodeposited 3D air-lifted Cu/Co metaconductor inductors with various lengths (b) ranging from 200 μm to 400 μm, and (c) SEM image of the cross-section of the fabricated inductor.

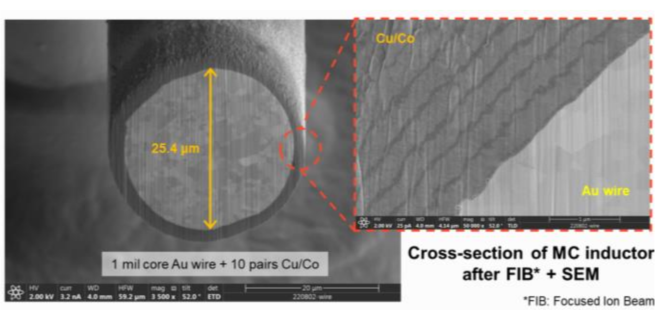

Figure 5: Cross-section image of the bonding wire structure plated with 10 pairs of Cu/Co after FIB milling.

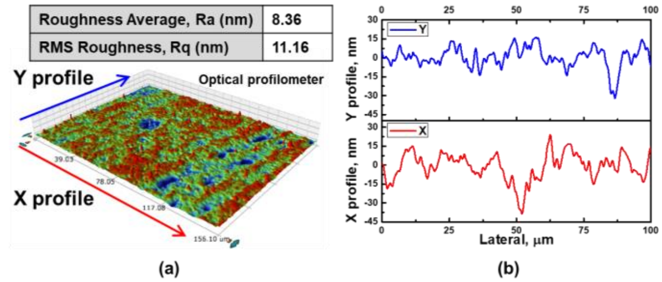

Figure 6: Surface profile of the CPW feeding line using the optical profilometer.

RF Performance

To evaluate the RF performance of the fabricated air-lifted Cu/Co metaconductor inductors, a vector network analyzer (VNA, HP E8316A, Agilent Inc.) is utilized after performing the standard CS-150 calibration procedure (short-open-load with a 50-ohm termination) between 100 MHz and 50 GHz. A ground-signal-ground (GSG) probe with a 150 μm pitch was used for the measurements. This section delves into the key parameters measured: inductance, RF resistance, and Q-factor.

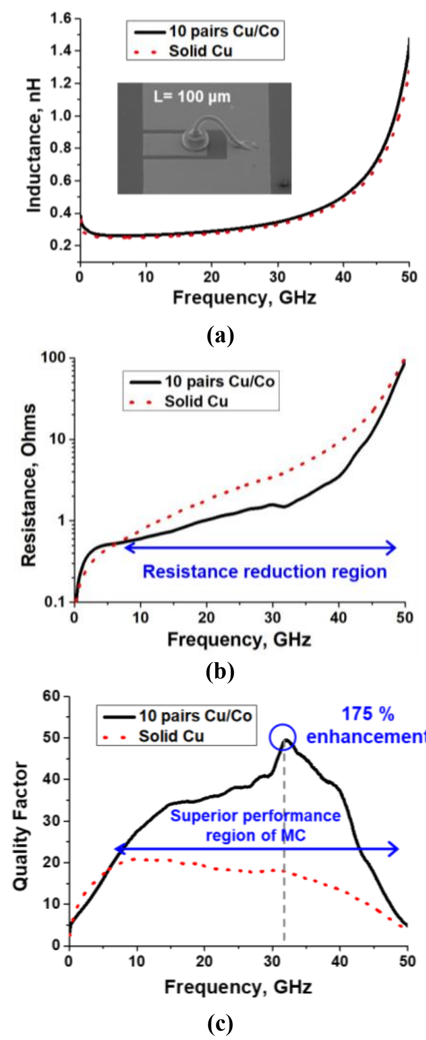

Figure 7: RF characterization of the air-lifted Cu/Co metaconductor-based inductors with a length of 100 μm, (a) inductance, (b) RF resistance, and (c) Q factor.

Figure 7(a) presents the extracted inductance values for both the solid Cu (red dashed line) and Cu/Co inductors (black solid line). The results show a high degree of similarity in inductance between the two materials, with a maximum difference of only 5%. This finding suggests that incorporating the Cu/Co metaconductor has a minimal impact on the overall inductance of the inductors at this specific length scale (100 µm).

The comparison of the RF resistance for the fabricated Cu/Co inductor and its Cu counterpart is shown in Figure 7(b). A decrease in RF resistance is observed for the Cu/Co metaconductor device compared to the solid Cu counterpart, particularly starting around 10 GHz. This decrease becomes more prominent as the frequency increases, reaching a maximum reduction at around 32 GHz.

In Figure 7(c), the Q-factor of the fabricated device is plotted. Here, the Cu/Co inductors demonstrate a significant improvement over their solid Cu counterparts. The maximum enhancement observed is a remarkable 175.5%, reaching a Q-factor value of 49.4 at 31.8 GHz. This significant improvement suggests that the Cu/Co metaconductor design effectively reduces RF conductor losses within the inductor, leading to superior RF performance at millimeter-wave frequencies.

AUTOMATED BINARY ELECTROPLATING SYSTEM

This section introduces an automated electroplating system (AES) designed specifically for fabricating binary metaconductors. These materials boast unique properties due to their alternating layers of two distinct materials. The system offers significant advantages over manual methods, particularly for researchers and manufacturers working with these materials.

The core of the AES lies in its automated control. A three-axis linear motion system precisely positions the substrate within the electroplating bath, ensuring a uniform layer across the entire sample. This controlled movement is crucial for binary layer deposition, allowing the system to switch between the two separate plating baths containing solutions for each material in the metaconductor. A source meter meticulously regulates the electrical current supplied to each bath independently, enabling precise control over the thickness of each deposited layer.

The AES eliminates the potential for human error during the critical steps of switching between solutions and controlling deposition parameters. A custom-designed, user-friendly graphical user interface (GUI) on a computer allows researchers to program the desired plating sequence.

Automation offers several advantages over manual methods. Fabrication time is significantly reduced, and the consistent execution of the programmed sequence ensures highly reproducible results across multiple fabrication runs. This consistency is crucial for reliable and high-performance metaconductor devices.

Figure 8 shows the proposed AES (a) and Cu/Co metaconductor CPW devices fabricated using the AES (b), visually demonstrating the system's capability to successfully produce binary metaconductor structures.

Future development of the AES could involve expanding its functionality to handle even more complex plating sequences and a wider range of materials. Additionally, integrating the system with characterization tools would enable automated data collection on the plated layers and provide real-time feedback on the plating process, allowing for further optimization of the fabrication process.

By refining and expanding the capabilities of the AES, researchers can significantly advance the field of metaconductor fabrication, paving the way for the creation of novel and high-performance devices with tailored properties.

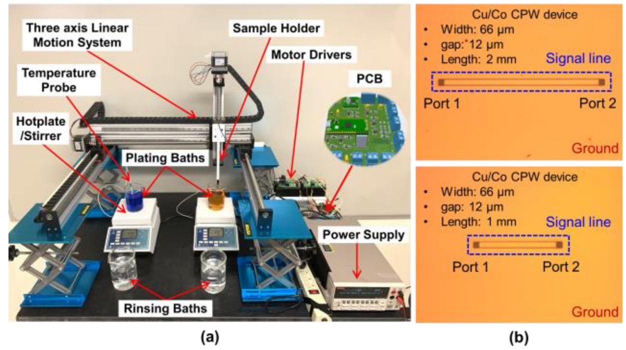

Figure 8: (a) optical image of the AES for binary metaconductor fabrication and (b) optical microscope image of the fabricated Cu/Co metaconductor CPW devices using the AES.

CONCLUSION

This research introduces highly efficient 3D inductors designed for millimeter-wave applications. These inductors are made with 10 pairs of Cu/Co metaconductors. The unique structure of the metaconductor, combining ferromagnetic and non-ferromagnetic metals, is instrumental in addressing the skin effect, thus reducing RF resistance, and minimizing conductor loss at the desired frequency. The air-lifted structure further reduces the dielectric losses of the system. Compared to conventional copper inductors, the Cu/Co metaconductor counterparts demonstrate a remarkable 175% enhancement in Q-factor at 32 GHz. Also, we successfully demonstrated a cost-effective and widely applicable fabrication method, automatic alternating electrodeposition, for manufacturing binary metaconductor devices. This technique can increase the applicability of metaconductor applications.

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