Vertically-Aligned Nano-Scale Integrated Inductors

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***Abstract* — We demonstrate a novel method to realize ultra-miniaturized on-chip vertical inductors for use in microwave and millimeter-wave devices. The inductor consists of a thin film of closely-packed, vertically aligned nickel nano-posts. The film is fabricated using a glancing angle physical vapor deposition method, which is CMOS compatible.**

The resulting nanostructured inductors were measured from 10 GHz to 70 GHz and were found to have inductances of 0.1 nH, resulting in $6\,\mathrm{pH}\cdot\mu\mathrm{m}^{-2}$, 60 times larger than previously reported planar inductors. A quality factor of 3 is measured and the results indicate that it continues to improve above 70 GHz, while inductance remains constant. Such nanostructured posts could potentially lead to ultra-small, ultra-wideband inductors to preserve space in integrated circuits.

***Index Terms* — Inductors, millimeter wave measurements, magnetic materials, glancing angle deposition.**

I. Introduction

Electronic components have been steadily scaling down to increase circuit density, reduce power requirements and increase circuit capabilities. However, inductor designs have been unable to keep up with the scaling-down process of other on-chip components. For discrete devices, solenoid and toroid structures are known to produce good quality factors and inductances; however, these structures are 3-dimensional and require many process steps to implement on-chip [1].

Typical 2-dimensional designs (eg. planar spiral inductors) have low inductances and quality factors, are highly dependent on substrate parameters and occupy large areas compared to other circuit elements [2]. Modern 2D (multi-layer) inductor structures can only achieve $0.1\ \mathrm{pH}\cdot\mu\mathrm{m}^{-2}$ [3], and have areas ranging from $10^4\ \mu\mathrm{m}^2$ to $5\ \mathrm{mm}^2$ [2].

Several efforts to develop nanoscale inductors using novel techniques and materials have increased inductance. One common technique uses carbon nanotubes as inductors [4]. While carbon inductors can theoretically produce very high inductances and quality factors, circuit integration remains challenging [5]. Alternatively, stress-induced coiled film inductors produce a very high inductance, but are narrowband with a self-resonance of about 300MHz and require specialized, difficult to scale fabrication techniques [1].

In this paper, we demonstrate that magnetic vertically aligned nano-wire films can be used to produce area efficient inductors for use in radio frequency applications. The potential for ultra-small inductors opens up new opportunities for chip designers when inductors would traditionally have been passed-over due to cost constraints. This paper will explain the inductor's fabrication technique and operating principles. The fabricated device has a an area of 6 pH·µm^{-2}, 60 times more inductance per area than the reported 2D micro-machined results in [3], which highlights the potential of these films for use as integrated inductors.

II. Fabrication of Vertically Aligned Magnetic Inductors

The proposed inductor films can be deposited by the glancing angle deposition (GLAD) technique. GLAD-deposited films have nanoscale features which can be controlled though substrate rotation and deposition angle [6]. The types of structures possible through GLAD include posts and helices, useful for inductor applications. Figure 1 shows a helix array that was deposited using the GLAD technique, demonstrating the high level of control that is achievable over the film structure. The individual structures in the film have nanometer-scale cross sections, which makes them suitable for low-area inductive elements.

In addition, GLAD films are fabricated using reliable physical vapor deposition (PVD) processes [6] which are compatible with existing CMOS technologies. The ease of the GLAD process is a distinct advantage over other nanotechnology-based devices for inductors, which often require electron-beam lithography [5], atomic force microscopy [7], or other methods unsuitable for mass-manufacturing [1].

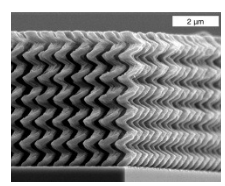


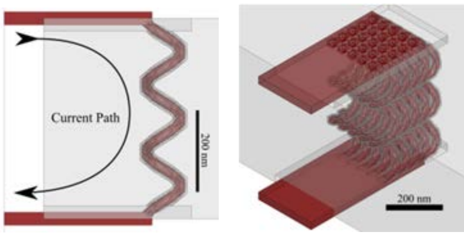
Figure 1: A regular helix array created using the GLAD technique.

III. Principles of Operation

We propose using highly packed magnetic vertical nanowires, similar to Figure 2, to develop area efficient inductors. There are two characteristics that distinguish this type of structure from traditional materials: anisotropic conductivity and high permeability.

A. Anisotropic Conductivity of the Surrounding Medium

The film is constructed of individual nickel nano-wires which stand perpendicular to a substrate's surface as shown in Figure 2b. In these films, the helices form an array of closely-packed nanowires, with sub-wavelength spacing. This fine structure means that the material can be treated as an effective medium. This effective medium has an anisotropic vertical conductivity and an effective permeability. Figure 3 shows the simulation results of a single inductor embedded in free space, bulk nickel film and anisotropic environment to demonstrate the dependency of the inductance on the surrounding medium. The film was modeled in ANSYS HFSS 15 by a single helix element embedded in a conductive homogeneous material.



(a) (b)

Figure 2: (a) Model of a single helix element (red) embedded in a uniform anisotropic film (grey). The vertical line visible on the left side is the port plane. (b) Model of a helix array.

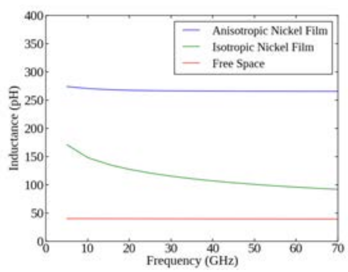


Figure 3: Inductance of a single helix embedded in a uniform material, shown in Figure 2a.

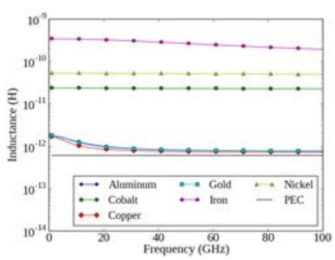


Figure 4: Inductance of a single helix in free space. This plot shows the dependence of the inductance of the single coil on the coil material.

The helix was separated from the bulk film by a thin gap to prevent the helix from being shorted by the film. The simulation shows that with all other parameters held constant, the anisotropic film has a higher inductance than the bulk nickel film. The anisotropic nickel film has the same parameters as a bulk nickel film, except that it is only conductive in the direction along the axis of the helix.

This film nanostructure additional advantages, including reduced eddy current effects. It is well known that the use of ferromagnetic materials in inductor core structures can greatly increase a device's inductance. However, ferromagnetic devices are not widely used in integrated devices due to high eddy currents and loss [8]. In our structure, these eddy currents are significantly reduced due to the film's anisotropic conduction, leading to higher inductance values than a bulk nickel film, as shown in Figure 3.

B. High Permeability

Since the individual nickel helical nanowires have a diameter which is smaller than the skin depth, the material characteristics of individual posts become a significant factor in the film's performance. Figure 4 shows the performance of a single helix made of various materials in free space, demonstrating that the inductance of the proposed film is heavily dependent on the material used for the helices. While iron shows the best performance, it also exhibits difficult to control material kinetic effects [9] which make it less suitable for this initial proof-of-concept experiment. Therefore, in this work, nickel has been used as the film material whereas iron could potentially show improved performance.

IV. Fabrication and Measurement

To validate the above simulations, an anisotropic film with a thickness of approximately 500 nm was fabricated and characterized. Figure 5 shows a cross section of the nano-scale structure of the fabricated nickel film, including the semi-separated closely-packed nature of the posts. The film was grown on top of closely-spaced gold lines (100 nm thickness) that were embedded in a 1 µm silicon dioxide layer, grown on a low resistivity silicon substrate. Figure 6 shows a schematic of the full test structure, including substrate layers.

To measure the film's inductance, it was necessary to connect the film's top side with a conductive capping layer. It is possible to grow a capping layer directly on the GLAD during the initial growth step [6]; however, this was not done for our samples to facilitate the lift-off procedure used to isolate the devices in the direction perpendicular to the gold traces. Instead, silver epoxy was applied as a post process to form a capping layer and later extracted from the measured results. Characterization with a scanning electron microscope has verified that the silver flakes in the epoxy lie on top of the film with no penetration. The epoxy material itself is not conductive, thus the silver epoxy provides a good capping layer. After fabrication, the S-parameters of the device were measured from 10 GHz to 70 GHz. From these measurements, the parasitic effects of the test traces and capping layer were extracted.

Figure 7 shows the extracted inductance for the layout shown in Figure 6. As expected from simulations in Figure 4, the inductance is constant over a bandwidth of 60 GHz, indicating that this inductor is extremely broad-band. The measured results show 0.1 nH of inductance for a closed path from signal to ground. Figure 8 shows the current distribution on the isotropic material; the current penetrates into the film about 5 µm from the port, indicating that the skin effect applies to the anisotropic material. The restricted current flow indicates that the portion of the material that contributes to the inductance is reduced from the physical area. Considering the

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reduced area and the results in Figure 7, the proposed structure results in 6 $\mathrm{pH} \cdot \mu\mathrm{m}^{-2}$ which is 60 times larger than the value reported in [3] for conventional 2D micro-inductors.

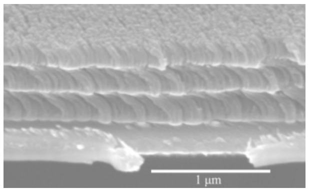
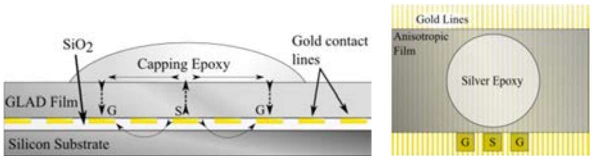


Figure 5: SEM image of the nanostructure of the film.



(a) (b)

Figure 6: a) Cross section of the test structure. The dashed lines show the current paths and the G-S-G labels indicate the probe configuration. b) Top-down view of the structure. The silver epoxy lies directly on top of the anisotropic film and does not contact the substrate or test lines.

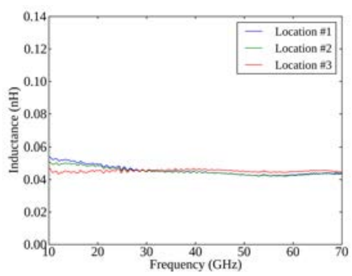


Figure 7: Extracted inductance value for a single signal to ground return path.

Another advantage is that patterning the film as well as altering the film height can tailor the inductance of the film. For instance, for the values shown here at 40 GHz, the resulting reactance is 22.6 Ω; therefore, to achieve an impedance of 50 Ω would require either devices connected in series or a film that was 2 times thicker (≈ 1 µm).

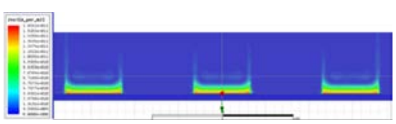


Figure 8: Current distribution at 70 GHz in the film when modeled with an anisotropic material. The maximum depth of current penetration at this frequency is approximately 5 µm.

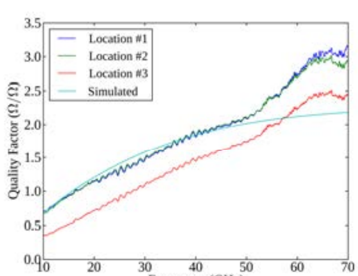


Figure 9: Measured and simulated quality factor for the film.

For the frequencies measured, the resistance was less than 18 Ω, including the contact resistance between the film and the gold-silver contacts. This leads to the quality factor in Figure 9. The quality factor linearly increases up to 70 GHz (reaching 3), indicating that the performance of these inductors may continue to improve above 70 GHz.

V. Conclusion

This paper introduces a novel inductor device based on nano-scale structures. These closely-packed structures produce an effective medium with anisotropic conductivity, which has the potential to produce inductors of up to 0.1 nH with an inductance density of 6 $\mathrm{pH} \cdot \mu\mathrm{m}^{-2}$. This density is considerably higher than previously reported densities. The proposed vertical nanostructures were fabricated using a glancing angle PVD method that is compatible with CMOS technology. The proposed structure could potentially lead to ultra-miniaturized wideband inductors and preserve space in integrated circuits.

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