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3D Coating of Interface Materials for High-Performance RF Passive Devices

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Abstract

The demand for high-performance Radio Frequency (RF) passive devices has been steadily increasing due to the growing complexity and sophistication of wireless communication systems. The Quality factor (Q-factor) is a key parameter for describing the signal losses and the energy efficiency of resonators. Previous studies have been done on the spin coating technique of intermediate coating, which presented some limitations in terms of 3D resonators. In this master thesis, we investigate the development of an intermediate layer using dip coating to enhance the Q-factor, i.e., the performance of RF passive devices.

The dip coating method is applied to add a nano ceramic coating to the 3D structure as the intermediate layer between the resonator ceramic substrate and the conductive silver coating. After the fabrication process, the samples are observed under Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM) and tested with Vector Network Analysis (VNA). Analysis and calculations are mainly conducted with the software Matlab and Gwyddion. The proposed technique improves the smoothness of the samples by 78.95%, and the Q-factor is tested to have a 20.87% enhancement using VNA.

The results demonstrate that the intermediate layer with the dip coating technique significantly improves the performance of RF passive devices by reducing the roughness of the resonator surface. These findings open up new opportunities for the design and development of high-performance RF passive devices in various applications, including wireless communication systems, radar systems, and satellite communication. Further studies can be carried out to reduce defects during fabrication and to stabilize the performance of the silver coating.

Keywords

Ceramic coating, Dip coating, Radio frequency, Passive RF devices, Quality factor
Efterfrågan på högpresterande passiva RF-enheter har stadigt ökat på grund av den växande komplexiteten och sofistikeringen hos trädlösa kommunikationssystem. Q-faktorn är en viktig parameter för att beskriva signalförluster och energieffektivitet hos resonatorer. Tidigare studier har gjorts på spin coating-tekniken för intermediära beläggningar, vilket presenterade vissa begränsningar för 3D-resonatorer. I denna masteruppsats undersöker vi utvecklingen av ett intermediärt lager med hjälp av doppbeläggning för att förbättra Q-faktorn, det vill säga prestandan hos passiva RF-enheter.

Doppbeläggningstekniken tillämpas för att lägga till en nanokeramisk beläggning på 3D-strukturen som intermediärt lager mellan resonatorns keramiska substrat och den ledande silverbeläggningen. Efter tillverkningsprocessen observeras proverna med SEM och AFM och testas med VNA. Analys och beräkningar utförs främst med programvaran Matlab och Gwyddion. Den föreslagna tekniken förbättrar provernas slätthet med 78.95%, och Q-faktorn testas och visar en förbättring med 20.87% med hjälp av VNA.

Resultaten visar att det intermediära lagret med doppbeläggningstekniken signifikant förbättrar prestandan hos passiva RF-enheter genom att minska ojämnheten på resonatorns yta. Dessa resultat öppnar upp nya möjligheter för design och utveckling av högpresterande passiva RF-enheter inom olika tillämpningsområden, inklusive trädlösa kommunikationssystem, radarsystem och satellitkommunikation. Ytterligare studier kan genomföras för att minska defekter under tillverkningen och stabilisera prestandan hos silverbeläggningen.

**Nyckelord**

Keramisk beläggning, Dip-beläggning, Radiofrekvens, Passiva RF-enheter, Kvalitetsfaktor
Sammanfattning
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Chapter 1

Introduction

1.1 Background

In the ever-expanding landscape of wireless communication systems and electronic devices, resonators play a pivotal role in enabling efficient signal transmission and processing in the Radio Frequency (RF) domain. These resonators, often used in RF passive devices, form the core components of various applications such as wireless communication systems [1][2], radar systems [3][4][5], and satellite communication [5][6][7]. Achieving high-performance RF passive devices is critical to meet the demands of modern communication technologies, where the ability to minimize signal losses and optimize energy efficiency is of paramount importance.

The key parameter that quantifies the signal losses and energy efficiency of resonators is the Quality factor (Q-factor) [8]. A higher Q-factor implies lower signal losses and improved selectivity, making it a crucial metric in designing resonators for RF applications. Generally, the Q-factor of resonators can be enhanced by reducing dielectric loss, radiated loss, metal loss, surface morphology, etc. While the other factors count on the optimization of resonator designs, and metal loss has a dependence on the conductive coating layer, what is focused here is to minimize the surface roughness by dip-coating an intermediate layer on the original resonator substrate [9]. To achieve high Q-factor values and enhance the overall performance of RF passive devices, the development of innovative coating techniques has become an area of intense research.

Traditional 2D coating methods, such as spin coating, have been widely used to add intermediate layers to resonators, improving their performance to some extent [10][11]. However, they present certain limitations, particularly
in the context of 3D resonators, where conformal coating deposition becomes challenging. The demand for enhanced RF passive devices necessitates the exploration of novel coating techniques capable of addressing the limitations of traditional methods.

In this master thesis, we focus on investigating the development and application of a novel dip coating method to create a nano-ceramic intermediate layer on 3D resonators. Dip coating, a versatile technique in the realm of thin-film deposition, offers advantages in terms of uniformity, controllability, and adaptability for complex geometries like 3D resonators [12]. The primary aim of this research is to enhance the Q-factor and overall performance of RF passive devices by incorporating the dip coating technique into the fabrication process of an intermediate nano-ceramic layer.

To comprehensively analyze the impact of the proposed intermediate layer with the dip coating method, extensive characterization and evaluation of the coated resonators are performed. The samples are observed under Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM) to assess the coating uniformity and morphology. The resonators are subjected to rigorous testing using Vector Network Analysis (VNA) to quantify the Q-factor enhancement achieved.

1.2 Problem

To increase the RF performance of the original ceramic resonators, finding a way to reduce the surface roughness can serve as a breakthrough. Previously, the spin-coating technique was applied in the fabrication of the intermediate ceramic layer [13]. However, due to the 3D structure of the resonators, spin coating can be tedious as far as coating one side of the cuboid sample each time is considered. This project will look into the following question: Can dip coating of nano-ceramic coating as the intermediate layer improve the Q-factor of the resonator?

1.2.1 Original problem and definition

In this project, the surface roughness of the resonator is focused on for RF performance improvement. While the grain size of the original ceramic surface has a mean diameter of more than 1 µm under SEM, the addition of an nano-ceramic intermediate layer can spread the nanoparticles into the cracks and edges of the structure to make the surface morphology smoother. Dip
coating is a technique to simplify the 3D coating process and more applicable for industrial manufacturing.

1.2.2 Scientific and engineering issues

Scientifically, the thesis is going to reduce the roughness, which will be qualitatively and quantitatively analyzed with SEM and AFM. Besides, the Q-factor enhancement of the resonator will also be tested and analyzed with VNA.

1.3 Purpose

The main purpose of the project is to reduce the surface roughness of the resonators in order to reach at least 20% improvement of Q-factor compared to devices without intermediate layer. Researchers in the field of passive RF devices may find some ideas on improving the performance of ceramic RF devices.

1.4 Goals

The goal of this project is to improve the Q-factor by adding an intermediate nano-ceramic layer between the ceramic substrate and the conductive silver coating. This has been divided into the following five sub-goals:

1. Find the proper nano-ceramic coating for the intermediate layer fabrication.

2. Make the intermediate layer as uniform as possible with dip coating.

3. Improve the adhesion between the intermediate layer and the silver coating layer by applying (3-Aminopropyl)trithoxysilane (APTES) before silver paste.

4. Reduce the leakage due to the fabrication process of the silver coating layer.

5. Test the RF performance of the devices with VNA. Improve the Q-factor by at least 20%.
1.5 Research Methodology

Literature research will be done first, and the fabrication experiments will be conducted in the chemistry lab of the Electrum Laboratory in KTH Royal Institute of Technology, Kista. All experiments and chemicals included will be dealt with properly in the lab for safety and sustainability. Analysis of the surface will be conducted using SEM and AFM (with software, Gwyddion [14]) in KTH Royal Institute of Technology (KTH), Kista. Testing of the device performance will be done with a VNA in the RF lab of Huawei Technologies Sweden AB, while calculations and plots will be carried out in Matlab.

1.6 Delimitations

The connection between the sample and the SubMiniature version A (SMA) connector for VNA tests is still an issue [13]. The silver coating may peel off or wear out in this process. Moreover, after testing a sample, the connectors need removing directly using a plier, which will damage the sample and make it unable to be reused.

Furthermore, massive manufacturing and experiments with repeatability and performance tests are hard to conduct due to high cost as well as technical and time limitation.

1.7 Structure of the thesis

Chapter 2 presents relevant background information about RF passive devices. Chapter 3 presents the methodology and methods used in the thesis project. Chapter 4 explains the fabrication and testing procedures in detail. Chapter 5 shows the microscopy (SEM & AFM) observation results and the resonator performance test (VNA) results as well as the analysis and discussion. Chapter 6 gives the conclusion and introduces some future work.
Chapter 2

Background

This chapter provides some basic background information about Radio-Frequency Electronics (Section 2.1), Material Processing (Section 2.2) and Electronics Characterizations (Section 2.3). Besides, this chapter also introduces some related work (Section 2.4).

2.1 Radio-Frequency Electronics

RF electronics is a specialized field within the broader domain of electronics that deals with the design, analysis, and application of devices and circuits that operate at radio frequencies. Radio frequencies encompass a range of electromagnetic waves with frequencies typically ranging from about 9 kilohertz (kHz) to 300 Gigahertz (GHz) \[15\]. This frequency range covers various essential applications, including radio and television broadcasting, wireless communication, radar systems, satellite communication, wireless networking, and many other wireless technologies.

2.1.1 Resonators

Resonators are fundamental components used in various fields of electronics, including RF electronics that is focused in this project. They are devices designed to exhibit a specific resonant frequency, which is the natural frequency at which they vibrate or oscillate most efficiently. Resonators are essential for selecting, stabilizing, and filtering specific frequencies in electronic circuits, enabling them to perform various functions.

Resonators find applications in various electronic devices and systems \[16\], including:
1. Oscillators: Resonators are the heart of oscillators, which generate continuous waveforms at specific frequencies. These oscillators are used in clocks, timing circuits, frequency synthesizers, and wireless communication devices.

2. Filters: Resonators are essential components in RF filters used to pass certain frequencies while rejecting others. These filters are crucial in communication systems to select specific frequency bands and reject interference.

3. Sensors: Some resonators can be used as sensors, as their resonant frequency can change in response to external factors such as temperature, pressure, or humidity. These changes in frequency can be measured and used for sensing applications.

4. Signal Processing: In audio engineering and digital signal processing, resonators are used for equalization, filtering, and sound synthesis, where specific resonant frequencies are emphasized or attenuated.

The selection of a specific type of resonator depends on the application’s requirements, such as frequency stability, precision, size constraints, and cost considerations. As technology advances, researchers and engineers continue to explore new materials and design techniques to develop even more efficient and precise resonators for various electronic applications.

### 2.1.2 Quality Factor

The Q-factor is a fundamental parameter used to characterize the performance of resonators, which are devices designed to exhibit specific resonant frequencies. In the context of resonators, the Q-factor is a measure of how efficiently the resonator can store and release energy at its resonant frequency. It represents the ratio of the energy stored in the resonator during one cycle of oscillation to the energy dissipated in the same time frame.

A high Q-factor indicates that the resonator has low energy dissipation and can sustain oscillations for an extended period without losing much energy. On the other hand, a low Q-factor indicates that the resonator dissipates energy rapidly and has a broader resonance curve.

Mathematically, the Q-factor can be defined as the frequency-to-bandwidth ratio of the resonator [17]:

\[
Q = \frac{f_r}{\Delta f} = \frac{\omega_r}{\Delta \omega}, \tag{2.1}
\]
where $Q$ is the Q-factor, $f_r$ is the resonant frequency, $\Delta f$ is the Full Width at Half Maximum (FWHM) i.e. the bandwidth of the resonator, $\omega_r$ is the resonant frequency, and $\Delta \omega$ is the bandwidth of the resonator’s response curve (the range of frequencies around $\omega_r$ where the response is significant).

Key points about the Q-factor and resonators include:

- **Selectivity**: Resonators with high Q-factors have narrow bandwidths, making them more selective in frequency response. They are commonly used in filters to pass specific frequencies while rejecting others.

- **Losses**: The Q-factor is inversely proportional to the losses in the resonator. Low losses result in high Q-values and vice versa.

- **Applications**: The Q-factor is essential in various applications, such as in the design of high-quality oscillators, filters, and communication systems [18] [19]. For example, quartz crystal oscillators used in precision clocks and frequency references have high Q-factors to achieve stable and accurate frequencies.

- **External Factors**: The Q-factor of a resonator can be influenced by external factors such as temperature, mechanical stress, and electrical loading. These factors can cause the Q-factor to vary, impacting the performance of the resonator in different environments.

In summary, Q-factor is a critical parameter in the analysis and design of resonators. It provides valuable insights into the resonator’s efficiency and selectivity, making it a key consideration in various electronic applications where precise frequency control and signal processing are essential.

### 2.2 Material Processing

Material processing is a broad and interdisciplinary field that focuses on the techniques, methods, and technologies used to alter the properties, shape, and structure of materials [20]. It plays a crucial role in manufacturing, research, and development of various products across industries, ranging from electronics and aerospace to automotive and biomedical.

#### 2.2.1 Dip Coating

One of the main objectives of material processing is surface modification. Surface treatments, such as coatings, plating, and etching, are part of
material processing, aimed at altering the surface properties of materials without affecting their bulk properties. These surface modifications improve wear resistance, corrosion resistance, and other surface-related characteristics [21][22]. In this thesis project, the dip coating technique is applied for coating an intermediate layer on the resonator.

Dip coating is a simple and widely used method of applying thin films or coatings onto the surface of objects. It is a versatile and cost-effective technique employed in various industries for both industrial and research purposes. Dip coating involves immersing an object or substrate into a liquid coating material and then withdrawing it at a controlled speed, leaving a uniform and continuous coating on the surface.

The dip coating process typically follows these basic steps [23]:

1. Preparing the Coating Solution: The coating material, often in the form of a liquid solution or suspension, is prepared. This solution contains the desired coating material, such as paint, varnish, polymer, or a chemical solution used for surface modification.

2. Cleaning and Preparing the Substrate: The substrate, which can be made of various materials like metal, glass, ceramic, or plastic, needs to be thoroughly cleaned to ensure proper adhesion of the coating. Any contaminants or residues on the substrate surface must be removed.

3. Immersing the Substrate: The cleaned substrate is carefully immersed into the coating solution. The speed and angle of immersion can affect the thickness and uniformity of the resulting coating.

4. Controlled Withdrawal: After a specific dwell time in the coating solution, the substrate is slowly and uniformly withdrawn at a controlled speed. As the substrate leaves the solution, the excess coating material drips off, leaving a uniform layer adhered to the substrate’s surface.

5. Drying or Curing: Depending on the type of coating material used, the coated substrate may require drying or curing to set the coating and achieve the desired properties. This can involve air drying, heating, or exposure to Ultraviolet (UV) light.

Dip coating is valued for several reasons [24]:

- Uniform Coating: The dip coating process typically results in a uniform and consistent coating thickness across the entire surface of the object.
• Cost-Effective: It is a relatively simple and cost-effective coating method compared to more complex techniques like spray coating or vapor deposition.

• Suitable for Complex Shapes: Dip coating is well-suited for coating objects with intricate shapes, as the coating solution can easily flow into crevices and contours.

• Wide Range of Coating Materials: Dip coating can be used with various coating materials, such as paints, adhesives, protective coatings, and even functional coatings like hydrophobic or hydrophilic layers.

Applications of dip coating can be found in numerous industries, including manufacturing, automotive, electronics, aerospace, and medical devices. It is commonly used for coating items like metal parts, glassware, medical implants, electronic components, and many other objects that require a thin, uniform, and protective coating. And the dip coating of nanoparticles has also attained great achievements in recent decades [25][26].

2.3 Electronics Characterizations

Electronics characterization is a crucial aspect of electronic device development, manufacturing, and research. It refers to the process of analyzing and evaluating the electrical properties, performance, and behavior of electronic components, materials, and systems. The main objective of electronics characterization is to gain a comprehensive understanding of how electronic devices and materials function under various conditions, and to ensure their reliability and performance meet specific requirements.

Here the main techniques for electronics characterizations will be introduced.

2.3.1 Scanning Electron Microscope

The SEM is a highly versatile and user-friendly tool extensively used for surface analysis at the micro- and nanoscale. With lateral spatial resolution in the sub-nanometer range, magnifications up to 2,000,000×, and large depths of field, SEMs offer valuable insights into the surface topography and composition of various materials, such as metals, carbons, polymers, semiconductors, oxides, biological samples, and more.
Unlike other types of microscopes, SEM creates images by scanning a focused electron beam in a pattern, line by line. During this scanning process, interactions between the electron beam and the sample’s surface generate different signals, leading to several processes. The main types of signals in SEM are as follows:

- **Backscattered Electrons (BSE):** These electrons originate from the electron beam and scatter elastically off the atoms in the sample, losing minimal energy. BSE signals primarily provide compositional contrast.

- **Secondary Electrons (SE):** SEs are emitted from the atoms in the sample due to inelastic interactions with the electron beam. These electrons have lower energies and contribute to topographical contrast.

- **X-rays:** When the electron beam strikes the atoms in the sample, some inner-shell electrons may get excited and ejected. This creates an electron hole in the inner shell, which is subsequently filled by an electron from an outer shell with higher energy. The energy difference between these shells is released as X-rays, providing valuable compositional information about the sample.

The Zeiss Gemini Ultra 55 FESEM, where FE stands for field-emission is utilized in this project. This particular microscope incorporates a thermal field emission source, which involves a cathode emitting electrons when subjected to a substantial voltage gradient (several kV). Compared to thermionic emitters, field-emission emitters offer superior resolutions, larger magnifications, higher brightness, longer lifespan, and require less maintenance as the filament doesn’t need heating.

The Ultra 55 FESEM in this lab comes equipped with four detectors:

- The **Energy Selective Backscattered-detector (ESB)** is utilized for detecting BSE.

- The **Secondary Electron Scanning of SEM (SE2)** detector is used to detect SE.

- The **Immersion Lens Scanning of SEM (InLens)** detector is employed for simultaneous detection of both BSEs and SEs.

- The **Energy-dispersive X-ray Spectroscopy Detector (EDX)** is utilized to detect X-rays.

In this project, the **InLens** and **SE2** detectors will be used to analyze the surface morphology of the resonators.
2.3.2 Atomic Force Microscope

**AFM** is a technique used to analyze material surfaces with incredibly high resolution, reaching the atomic level. It is widely employed for studying roughness, step height, and surface profiles in various samples. The Veeco Nanoscope III AFM used in the project is mounted on a vibration damping table stage. The AFM offers three different modes for surface analysis:

- **Contact mode**: The tip is in close contact with the surface, applying a repulsive force using a piezoelectric element. This mode is sensitive to frictional forces and can potentially damage the sample and tip.

- **Non-contact mode**: The cantilever oscillates close to its resonant frequency 5-15 nm above the surface, detecting weak attractive Van der Waals forces. It avoids surface damage but is sensitive to contamination and unsuitable for liquid environments.

- **Tapping mode**: This scanning mode, employed in this project, utilizes a piezoelectric crystal to make the cantilever vibrate at or close to its resonance frequency. This vibration causes the tip to gently touch or tap the surface during each oscillation cycle, giving rise to the name "tapping mode." By employing this technique, both potential surface damage reduction and achieving high resolution can be accomplished. When the tip taps the sample’s surface, its oscillation amplitude decreases. This decrease in amplitude can be utilized to identify surface features. For instance, when scanning over a surface bump, the amplitude diminishes, whereas passing over a hollow leads to an increase in amplitude. A feedback loop is employed to maintain a constant amplitude of the tip, thereby keeping the distance between the tip and the sample, as well as the applied force to the sample, constant as well.

The tapping mode is designed to protect the sample surface from harm. The force exerted on the sample is vertical, preventing lateral pulling of the surface during scanning. This aspect is particularly crucial for delicate biological samples. The method is so gentle that it allows imaging of individual polymer molecules without altering their conformation throughout the scan.

Surface roughness measurement is a widely utilized application of **AFM**, being particularly significant in the precise control of epitaxial growth, where
minimizing roughness is crucial in active device layers. Additionally, AFM can be employed to measure step-height in structures featuring small elements. Hence, AFM in tapping mode is applied in this project for analysis of the surface roughness of the resonators.

2.3.3 Vector Network Analyzer

The VNA is a precision electronic instrument used to analyze and characterize the electrical properties of high-frequency and radio-frequency devices, circuits, and systems. It measures the amplitude and phase of electrical signals at different frequencies to determine the scattering parameters (S-parameters) of the device under test \[27\]. S-parameters provide crucial information about how the device responds to RF signals, including reflections, transmission losses, and signal quality. VNA\textsubscript{s} are essential tools in the design and testing of RF and microwave components, such as antennas, filters, amplifiers, and communication systems.

2.4 Related work

As this is the continuation of the previous research, Haomin’s master thesis builds the foundation of this project \[13\]. The main purpose of the two projects are generally the same, but there are several differences and improvements for sure. For instance, Haomin used TiO\textsubscript{2}/graphene as the coating solution of the intermediate layer, and the spin-coating technique was utilized while the dip-coating technique was introduced as an alternative option. Based on these points, refinements are dedicated on the choice of the nano-ceramic coating as well as the coating technique to attain improvements on the surface roughness and the Q-factor.

2.5 Summary

The rapid advancement of wireless communication technologies and the increasing demand for faster and more reliable wireless networks have driven significant developments in the field of radio-frequency electronics. RF engineers play a critical role in the design and optimization of wireless systems, enabling seamless connectivity and communication in our modern, interconnected world.
In addition, material processing is a constantly evolving field, driven by advances in technology and the need for new materials with improved properties and performance. Researchers and engineers continue to explore innovative processing methods to meet the demands of various industries and pave the way for cutting-edge technologies.

Besides, electronics characterization is essential in developing reliable and high-performance electronic devices, optimizing manufacturing processes, and advancing research in the field of electronics. The data and insights obtained through characterization techniques are valuable for improving device design, optimizing circuit performance, and enhancing the overall efficiency of electronic systems.

This project involves these field categories from fabrication to testing, and can also provide inspiration on the future research for the development of technologies.
Chapter 3

Methodology and Methods

3.1 Research Process

The main steps of this project are shown in Figure 3.2. Detailed procedures are introduced in Chapter 4, covering

1. Section 4.1: Fabrication of the intermediate layer,
2. Section 4.2: Fabrication of the adhesive layer,
3. Section 4.3: Fabrication of the silver coating layer, and
4. Section 4.4: Processes of RF testing.

Figure 3.1: Original resonator.
### 3.2 Sample Analysis

After the fabrication steps (before SMA connectors installation indicated in Figure 3.2), the sample is observed under SEM and AFM. The surface morphology will be analyzed, and the roughness will be calculated and compared with Gwyddion.

What’s more, after data is generated by VNA, plots and calculations will be carried out with Matlab.
Chapter 4
Fabrication and Testing

4.1 Intermediate Layer Fabrication

In this process, the MOLVCE ceramic coating from Jiyou Industrial is used for the intermediate layer. Since the solution is thin enough, it can be directly applied in the dip coating technique without dilution to form a relatively uniform coating.

The sample is first cleaned with Isopropanol (IPA) in an ultrasonic cleaner for 15 min to remove the dust and oils to ensure that the ceramic coatings can be firmly bound to the surface. After the degreasing step, the sample is blow dried with N₂. Instead of the spin coating technique applied before [13], dip coating is preferred due to the 3D structure of the resonators. With dip coating, the sample is immersed into the ceramic coating solution and sealed for 1 h. After the sample is taken out from the solution and blow dried, it is annealed at 375 °C for 1 h and cooled down naturally.

Before the silver coating layer fabrication process, the sample still needs a 700 °C annealing process for 1 h. The high-temperature oven used is a VEVOR furnace shown in Figure 4.1. This annealing step is able to remove the polymers in the ceramic coating.

4.2 Adhesive Layer Fabrication

Owing to the hydrophobic characteristic of the nano-ceramic coating, the conductive silver coating is hard to attach directly on it. Hence, this process is to add an adhesive APTES layer on the intermediate layer to make the silver coating form easier and firmer.
Figure 4.1: VEVOR furnace used for high-temperature annealing.

**APTES**, or (3-Aminopropyl)triethoxysilane (Figure 4.2), is a coupling agent with amino functionality that finds extensive use in various applications [28]. Its ability to create strong bonds between inorganic substrates and organic polymers makes it highly valuable. The silicon-containing part of the molecule enables robust adhesion to substrates, while the primary amine group reacts effectively with a wide range of thermoset, thermoplastic, and elastomeric materials. In this way, **APTES** can enhance the adhesion between the nano-ceramic coating layer and the silver coating layer [29].

![APTES structure](image)

**Figure 4.2**: (3-Aminopropyl)triethoxysilane structure.

The **APTES** is diluted with **IPA** to 10% (v/v) to reach a thinner adhesive layer. The dip coating technique is again used in this process. The sample with nano-ceramic coating is immersed in the **APTES-IPA** solution for 1 h in an 80 °C water bath. After the sample is taken out, a polyester wiper is used to wipe dry it.
4.3 Silver Coating Layer Fabrication

For the silver coating, the silver nanoparticles ink for screen printing from SigmaAldrich is diluted by the silver diluent from Agar Scientific. After mixing well, the silver paint is brushed onto the sample by a paintbrush and preheated on a hotplate at: a) 50 °C for 5 min, b) 70 °C for 5 min, and c) 100 °C for 25 min. The preheating process is aimed at improving the uniformity of the silver coating. The sample then goes through a 180 °C annealing process for 3 h, where the surface of the sample will turn white and reflective. Since more than 3 coating layers are required to obtain desired RF performances of the resonator, this whole coating process is also done in an iterative way. The annealing is carried out every time after painting to reduce the unexpected influence of the diluent in the former coating layer on the silver paste of the current layer. Besides, due to the boiling temperature of APTES being 217 °C, the annealing temperature must be lower than that to avoid the peeling off of silver coatings from the surface.

Note that the signal leakage will occur at those parts of the sample surface that is bared or with relatively thin silver coatings. The edges of the cuboid sample should especially be taken good care of as a result of surface tension. Therefore, an extra silver coating from Agar Scientific is added to the edges of the sample. This coating can dry up rapidly in the air, while the sample then receive a 100 °C heating process for 30 min for higher conductivity. The resistance of the surface is tested with a multimeter, reaching a range of 0.1 Ω to 0.3 Ω as expected. However, the silver coating may still have a negative feedback on the RF performances of the resonator, and hence the focus is set on the horizontal comparison between samples with the same silver coatings but with or without the intermediate layer.

4.4 RF Testing Process

In this project, the RF tests are carried out with a VNA from Keysight (Figure 4.3), where the transmitted signal (S21) data is measured.

Before being tested, two connectors are fixed onto the sample using a conductive epoxy from CircuitWorks with the help of a fixture. Figure 4.4 shows the samples with 2-port connectors of different angles and the fixtures. The samples are heated at 120 °C for 1 h to accelerate the curing process. After cooling down, the samples are ready to be tested on the VNA. The device is calibrated and the frequency range is set from 3.77 GHz to 3.87 GHz by
experience to find the peak.

Figure 4.3: Keysight N5222A PNA Microwave Network Analyzer, 26.5 GHz.

Figure 4.4: Samples with 2-port connectors and the fixtures.
Chapter 5

Results and Analysis

5.1 Surface Morphology

The basic goal of this project is to fabricate an intermediate layer on the resonator to reduce the surface roughness, which makes it critical to analyze the surface morphology. Hence, SEM and AFM are applied as surface characterization techniques.

5.1.1 SEM Characterization

As both the original ceramic sample and the sample with the ceramic coating are insulators, 50 nm of gold is plated on one side of the cuboid sample before SEM observation, which will not cover up the actual surface characteristics of the samples [30]. While silver definitely has high conductivity, there is no need for the sample with silver coating to be gold-plated.

Figure 5.1 shows the SEM images of the samples with and without the intermediate layer in InLens and SE2 scanning mode under 10K× and 130K× magnification. According to Figure 5.1a and 5.1b, the grain size of the ceramic is observed to vary in micrometer scale, with obvious lumps and blocks on the surface. When the magnification is increased to 130K× (Figure 5.1c and 5.1d, the ceramic nanoparticles can be clearly seen. The irregular lumpy structures, however, are still there, showing great roughness. In comparison, the sample with the nano-ceramic coating has a much smoother surface according to Figure 5.1e and 5.1f. Though the surface also has some ups and downs, the cracks, edges and corners have been significantly reduced. The improvement can be even better observed from Figure 5.1g and 5.1h, where the scale goes down to nanometer. After 700 °C annealing (Section 4.1),
polymers have been removed by high temperature, and the coating turns to ceramic. The nanoparticles of the ceramic coating layer are clear and relatively even, without lumps and cracks.

Besides, Figure 5.2 shows the samples with the conductive silver coating in InLens and SE2 scanning mode under 1K×, 5K×, 10K× and 130K× magnification. From the SEM images, the surface of the silver coating is relatively flat and even. The ceramic surface characteristics are no longer observed since the thickness of the silver coating layer is necessary to be more than 6-7 µm in order to prevent leakage in the RF test. Holes can be seen from either magnification, which may be due to the gases escaped from the coating in the annealing process.

5.1.2 AFM Characterization

While SEM images give a straightforward understanding of the improvement on surface smoothness, the AFM characterization can provide 3D information and quantitative analysis on the roughness measurements.

AFM images of the original sample and 2 samples with the intermediate layer are shown in Figure 5.3. From the 3D models, smoother edges and flatter surfaces can be seen. Notice that the height has different scale rulers for each model.

In order to acquire quantitative results of roughness, the AFM files are further analyzed using Gwyddion for detailed information. The average roughness $R_a$ and the Root Mean Square (RMS) roughness $R_q$ of the samples are listed in Table 5.1. The average reduction of $R_a$ and $R_q$ are 78.95% and 78.06% respectively for sample 1 and sample 2 with the nano-ceramic coating, showing great improvement on the surface morphology. In the same time, as a comparison to data in the previous work where the reduction value is 54.4%, the smoothness is further enhanced [13].

<table>
<thead>
<tr>
<th></th>
<th>Original Sample</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Roughness $R_a$</td>
<td>250.5 nm</td>
<td>48.94 nm</td>
<td>56.53 nm</td>
</tr>
<tr>
<td>$R_a$ Reduction</td>
<td>/</td>
<td>80.46%</td>
<td>77.43%</td>
</tr>
<tr>
<td>RMS Roughness $R_q$</td>
<td>303.3 nm</td>
<td>63.59 nm</td>
<td>69.48 nm</td>
</tr>
<tr>
<td>$R_q$ Reduction</td>
<td>/</td>
<td>79.03%</td>
<td>77.09%</td>
</tr>
</tbody>
</table>

Figure 5.4 shows the comparison of texture and roughness along a cutline across the AFM image of the samples. From the texture comparison graph
Figure 5.1: SEM images. (a)-(d) Original sample; (e)-(h) Sample with the intermediate layer.
Figure 5.2: SEM images of the silver coating.
Figure 5.3: AFM images. (a)-(b) Original sample; (c)-(f) Sample with intermediate layer.
(Figure 5.4d), it can be observed that there are more dramatic height changes as to the original ceramic surface. The original sample has more sharp edges, leading to larger tangent slopes in the 1D texture graph. The contrast and improvement is more obvious regarding the 1D graph of roughness comparison (Figure 5.4e). This result is in accordance with the roughness data calculated and displayed in Table 5.1.

## 5.2 RF Performance

While the surface morphology is verified using SEM and AFM in the previous section, the RF performance of the resonator is tested by a VNA. The results of S21 measurements are processed in Matlab and shown in Figure 5.5. The values of the peaks and -3 dB bandwidth (BW) points have been marked on the graph. For a higher Q-factor, the waveform typically has a sharper peak. This phenomenon holds for the samples with the ceramic coating layer.

Furthermore, the unloaded and compensated Q-factor of resonators can be found with equations:

\[
Q = \frac{f_T \text{ (MHz)}}{\Delta f \text{ (MHz)}},
\]

and

\[
Q_c = \frac{Q}{1 - 10^{A/20}},
\]

where \( f_T \) is the resonance frequency, \( \Delta f \) is the -3dB BW frequency, and \( A \) is the magnitude value of the amplitude of the peak. The calculation results are presented in Table 5.2. For the original samples, the average Q-factor is 1466.38. The Q-factor improvements of sample 1, sample 2 and sample 3 are 17.46%, 24.67% and 20.48% respectively, with an average of 20.87%. This result generally prove the enhancement of RF performances brought by addition of the intermediate layer.

A normalization of the RF performance data is presented in Figure 5.6. From the normalized plot, samples with intermediate layer shows narrower span (2.26 MHz) compared to the original samples (2.65 MHz), in accordance with the previous results.

For better analysis of the successful rate of the intermediate layer coating technique, Figure 5.7 shows the 4 unsuccessful cases among the total 9 samples in the same batch, while the other 2 samples do not show any meaningful waveform. The results are presented in Table 5.3. These cases all have magnitude of losses far larger than -40 dB, which are not meaningful for analysis and comparison with the original resonator. Figure 5.8 presents a
Figure 5.4: 1D analysis of AFM characterization. (a)-(c) Samples with 1D cutlines to be analyzed. (d)-(e) 1D graph of texture and roughness comparison.
Figure 5.5: Waveform of S21 measurements for samples with and without intermediate layer (successful cases).

Table 5.2: Results of RF two-port S21 measurements (successful cases).
*Original - Original Sample.

<table>
<thead>
<tr>
<th></th>
<th>Original 1</th>
<th>Original 2</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_T$ (MHz)</td>
<td>3832.08</td>
<td>3819.70</td>
<td>3800.88</td>
<td>3814.10</td>
<td>3816.13</td>
</tr>
<tr>
<td>$f_{right}$ (MHz)</td>
<td>3833.35</td>
<td>3820.95</td>
<td>3802.00</td>
<td>3815.19</td>
<td>3817.25</td>
</tr>
<tr>
<td>$f_{left}$ (MHz)</td>
<td>3830.65</td>
<td>3818.35</td>
<td>3799.75</td>
<td>3813.06</td>
<td>3815.00</td>
</tr>
<tr>
<td>$\Delta f$ (MHz)</td>
<td>2.7</td>
<td>2.6</td>
<td>2.25</td>
<td>2.13</td>
<td>2.25</td>
</tr>
<tr>
<td>$A$ (dB)</td>
<td>-35.0725</td>
<td>-37.9375</td>
<td>-34.3207</td>
<td>-33.7694</td>
<td>-27.9668</td>
</tr>
<tr>
<td>$Q_{vna}$</td>
<td>1418.89</td>
<td>1466.41</td>
<td>1680.25</td>
<td>1791.20</td>
<td>1696.40</td>
</tr>
<tr>
<td>$Q$</td>
<td>1419.29</td>
<td>1469.12</td>
<td>1689.28</td>
<td>1790.66</td>
<td>1696.06</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>1444.77</td>
<td>1487.99</td>
<td>1722.40</td>
<td>1828.11</td>
<td>1766.66</td>
</tr>
</tbody>
</table>
Figure 5.6: Normalized waveform of S21 measurements for samples with and without intermediate layer (successful cases).

A straightforward plot of the 7 out of 9 samples with 3 layers of silver coating. The horizontal line is the compensated Q-factor of the original resonator, and the vertical line represents the -40 dB loss. They both serve as a landmark. Considering the samples with loss lower than -40 dB and meanwhile have a Q-factor improvement compared to the original sample, the 3 samples (sample 1, sample 2 and sample 3) on the upper-right corner manage to fulfill the requirements. From this point, the successful rate is 3 out of 9, that is 33.33%, while 2/9 have too large losses, 2/9 have no Q-factor improvement, and 2/9 broken before or during testing.

Table 5.3: Results of RF two-port S21 measurements (unsuccessful cases).

<table>
<thead>
<tr>
<th></th>
<th>Original Sample</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
<th>Sample 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_T$ (MHz)</td>
<td>3832.08</td>
<td>3803.93</td>
<td>3814.08</td>
<td>3825.09</td>
<td>3815.49</td>
</tr>
<tr>
<td>$f_{right}$ (MHz)</td>
<td>3833.35</td>
<td>3804.95</td>
<td>3815.01</td>
<td>3827.28</td>
<td>3817.80</td>
</tr>
<tr>
<td>$f_{left}$ (MHz)</td>
<td>3830.65</td>
<td>3802.65</td>
<td>3813.10</td>
<td>3823.28</td>
<td>3813.50</td>
</tr>
<tr>
<td>$\Delta f$ (MHz)</td>
<td>2.7</td>
<td>2.3</td>
<td>1.91</td>
<td>4</td>
<td>4.3</td>
</tr>
<tr>
<td>$A$ (dB)</td>
<td>-35.0725</td>
<td>-63.0833</td>
<td>-53.5689</td>
<td>-49.5855</td>
<td>-48.6609</td>
</tr>
<tr>
<td>$Q$</td>
<td>1419.29</td>
<td>1653.88</td>
<td>1996.90</td>
<td>956.27</td>
<td>887.32</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>1444.77</td>
<td>1655.04</td>
<td>2001.10</td>
<td>959.45</td>
<td>890.61</td>
</tr>
</tbody>
</table>
Figure 5.7: Waveform of S21 measurements for samples with and without intermediate layer (unsuccessful cases).

Figure 5.8: Q-factor vs. magnitude (dB) plot of the 7 samples with 3-layer silver coating.
Apart from the 3-layer silver coating, 1- and 2-layer have also been tried. The typical waveform can be seen from Figure 5.9 and Figure 5.10, and the calculated results are listed in Table 5.4 and Table 5.5. The comparison data between 1-, 2-, and 3-layer silver coating is listed in Table 5.6, where for 3-layer silver coating the average is used in terms of the Q-factor with intermediate layer. From the bar graph (Figure 5.11), it can be observed great improvement of the basis Q-factor when adding more layers of the conductive silver coating. The trend of improvement is slowing down from the experiments of 1 to 3 layers. Also is the case regarding the improvement given by the coating of the intermediate layer.

Figure 5.9: Waveform of S21 measurements for samples with and without intermediate layer (1-layer silver coating).

5.3 Discussion

In this discussion section, several challenges faced during the whole fabrication and testing process are presented. Among them, the most tricky one is the adhesion problem, including the adhesion between the intermediate layer and the conductive silver coating layer as well as between the silver coating layer and the SMA connectors. As for the former, APTES is added before the silver paste is painted onto the ceramic to enhance the
Table 5.4: Results of RF two-port S21 measurements (1-layer silver coating).

<table>
<thead>
<tr>
<th></th>
<th>Original sample</th>
<th>Sample with intermediate layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_T$ (MHz)</td>
<td>3839.75</td>
<td>3820.75</td>
</tr>
<tr>
<td>$f_{right}$ (MHz)</td>
<td>3846.13</td>
<td>3823.08</td>
</tr>
<tr>
<td>$f_{left}$ (MHz)</td>
<td>3832.75</td>
<td>3818.20</td>
</tr>
<tr>
<td>$\Delta f$ (MHz)</td>
<td>13.38</td>
<td>4.88</td>
</tr>
<tr>
<td>$A$ (dB)</td>
<td>-37.6739</td>
<td>-38.5023</td>
</tr>
<tr>
<td>$Q$</td>
<td>286.98</td>
<td>782.94</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>290.78</td>
<td>792.36</td>
</tr>
</tbody>
</table>

Table 5.5: Results of RF two-port S21 measurements (2-layer silver coating).

<table>
<thead>
<tr>
<th></th>
<th>Original sample</th>
<th>Sample with intermediate layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_T$ (MHz)</td>
<td>3815.71</td>
<td>3821.06</td>
</tr>
<tr>
<td>$f_{right}$ (MHz)</td>
<td>3817.60</td>
<td>3822.35</td>
</tr>
<tr>
<td>$f_{left}$ (MHz)</td>
<td>3813.40</td>
<td>3819.66</td>
</tr>
<tr>
<td>$\Delta f$ (MHz)</td>
<td>4.2</td>
<td>2.69</td>
</tr>
<tr>
<td>$A$ (dB)</td>
<td>-39.6932</td>
<td>-32.0727</td>
</tr>
<tr>
<td>$Q$</td>
<td>908.50</td>
<td>1420.47</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>918.01</td>
<td>1456.76</td>
</tr>
</tbody>
</table>
Table 5.6: Results of RF two-port S21 measurements (1-, 2- and 3-layer silver coating).

<table>
<thead>
<tr>
<th></th>
<th>$Q_c$</th>
<th>Improvement of basis</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original sample (1-layer)</td>
<td>290.78</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>With intermediate (1-layer)</td>
<td>792.36</td>
<td>/</td>
<td>172.49%</td>
</tr>
<tr>
<td>Original sample (2-layer)</td>
<td>918.01</td>
<td>215.71%</td>
<td>/</td>
</tr>
<tr>
<td>With intermediate (2-layer)</td>
<td>1456.76</td>
<td>/</td>
<td>58.69%</td>
</tr>
<tr>
<td>Original sample (3-layer)</td>
<td>1466.38</td>
<td>59.73%</td>
<td>/</td>
</tr>
<tr>
<td>With intermediate (3-layer)</td>
<td>1772.39</td>
<td>/</td>
<td>20.87%</td>
</tr>
</tbody>
</table>

Figure 5.11: Bar graph of 1-, 2- and 3-layer silver coating comparison.
bonds and adhesion between layers. Without APTES, the sample without the intermediate layer is not affected, but that with the hydrophobic nano-ceramic coating will repel the silver coating. Nevertheless, every process has advantages and disadvantages. The addition of the APTES solves the hydrophobicity problem of the nano-ceramic coating, and meanwhile sets more restrictions on the other procedures, such as the annealing temperature. The boiling point of APTES is 217 °C, which means the allowed temperature for annealing the silver coating and also the followed conductive epoxy needs to be controlled relatively low. When it goes to the installation of the connectors onto the resonators, welding is not taken into consideration also because of the temperature limitation. Under such circumstances, the conductive epoxy is used for conducting and fixing, while in order to ensure the firmness of installation, the certain fixture is specially assembled. If in the future, the silver coating is replaced or improved to be less fragile, the fixture step can be omitted by using welding.

Considering the other challenges, the dip coating method must be mentioned. In this project, the sample is submerged into the ceramic coating solution for 1 h, but the minimum time needed is not looked into, and the maximum time so that the intermediate layer will not be too thick is also not specified. For the nano-ceramic coating used in this project, the solution is thin enough for direct use without dilution. If further research requires the replacement of the ceramic coating recipe or specific thickness of the intermediate layer, the concentration and viscosity should be paid attention to.

Apart from what are mentioned above, the RF test results indicate some things for serious consideration. According to Figure 5.5 and Table 5.2, the samples with the intermediate layer show great improvements compared to the original resonator as well as to the previous work (11.5%) [13], and this is especially the case for sample 2. The curve of sample 2 can be observed to have larger noise than the others. Also, there appear some unsuccessful cases, either whose loss is larger than -40 dB or the Q-factor is even smaller than the original resonator. This may be caused by several factors: a) the uniformity of the intermediate layer after dip coating, b) the adhesion between the intermediate layer and the conductive silver coating layer, c) the leakage from the silver coating layer, and d) the connection between the sample and the connectors, as well as between the connectors and the cables.
Chapter 6

Conclusions and Future work

6.1 Conclusions

In this project, a nano-ceramic intermediate layer was successfully fabricated on the ceramic resonator. The improvement of surface roughness was studied with SEM and AFM, and also processed and calculated as quantitative proof. With around 78% reduction on roughness, the target of improving the surface morphology was greatly fulfilled. What’s more, the Q-factor was raised by 20.87% in average according to the VNA test results, which well demonstrates the RF performance enhancement thanks to the intermediate layer. Therefore, the thesis project managed to reach higher performances of RF passive resonators by means of adding an intermediate layer between the ceramic substrate and the conductive silver coating.

6.2 Limitations

The main goals of the project have been generally reached, but there still exist some issues and limitations. To begin with, since the intermediate nano-ceramic coating is hydrophobic, the silver paste is hard to be directly added onto it. For this reason, 10% APTES-IPA solution is first applied as a binder between layers. Since APTES has a boiling point of 217 °C, the follow-up annealing process must have a temperature lower than this value. This turns out to be a trade-off between the conductivity performance and the adhesion of the silver coating. While the silver coating process is not the focus of this project, samples w/o the intermediate layer but with the same silver coating treatment are compared horizontally to reduce the influence of the silver coating.
In addition, since the conductive epoxy is used to fix the SMA connector onto the sample, the RF performance may be lower than using the traditional welding method. Plus, the silver coating may peel off or wear out in the process of fixture installation. Moreover, the connectors are removed with a plier after testing in consideration of reusing the connectors. The samples, however, are "sacrificed" due to the damage caused by the "violent" disassembly.

6.3 Future work

For future work, a better application of the silver paste on hydrophobic and ceramic surfaces can be found and studied to reach a higher RF performance. The way to fix the SMA connectors on the resonators can be improved on the basis of the certain silver coating used. Also, if this technique is brought into manufacturing, the methods for massive production can serve as an entry point.

6.4 Reflections

Upon the attainment of the goals, it is also important to implement the concept of sustainable development and protect the environment. On one hand, the nano-ceramic coating solution can be preserved and reused, which is able to reduce the waste of chemicals and promote sustainability. On the other hand, dip coating is a method easier to carry out for 3D structures than spin coating. Fewer procedures are needed to coat all sides, and thus less power and energy is consumed.
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The demand for high-performance RF passive devices has been steadily increasing due to the growing complexity and sophistication of wireless communication systems. The $Q$-factor is a key parameter for describing the signal losses and the energy efficiency of resonators. Previous studies have been done on the spin coating technique of intermediate coating, which presented some limitations in terms of 3D resonators. In this master thesis, we investigate the development of an intermediate layer using dip coating to enhance the $Q$-factor, i.e., the performance of RF passive devices.

The dip coating method is applied to add a nano ceramic coating to the 3D structure as the intermediate layer between the resonator ceramic substrate and the conductive silver coating. After the fabrication process, the samples are observed under SEM and AFM and tested with VNA. Analysis and calculations are mainly conducted with the software Matlab and Gwyddion.

The proposed technique improves the smoothness of the samples by 78.95\%, and the $Q$-factor is tested to have a 20.87\% enhancement using VNA.
The results demonstrate that the intermediate layer with the dip coating technique significantly improves the performance of RF passive devices by reducing the roughness of the resonator surface. These findings open up new opportunities for the design and development of high-performance RF passive devices in various applications, including wireless communication systems, radar systems, and satellite communication. Further studies can be carried out to reduce defects during fabrication and to stabilize the performance of the silver coating.

Keywords: Ceramic coating, Dip coating, Radio frequency, Passive RF devices, Quality factor

Efterfrågan på högpresterande passiva RF-enheter har stadigt ökat på grund av den växande komplexiteten och sofistikeringen hos trådlösa kommunikationsystem. Q-faktorn är en viktig parameter för att beskriva signalförluster och energieffektivitet hos resonatorer. Tidigare studier har gjorts på spin coating-tekniken för intermediära beläggningar, vilket presenterade vissa begränsningar för 3D-resonatorer. I denna masteruppsats undersöker vi utvecklingen av ett intermediärt lager med hjälp av doppbeläggning för att förbättra Q-faktorn, det vill säga prestandan hos passiva RF-enheter.

Doppbeläggningstekniken tillämpas för att lägga till en nanokeramisk beläggning på 3D-strukturen som intermediärt lager mellan resonatorernas keramiska substrat och den ledande silverbeläggningen. Efter tillverkningsprocessen observeras proverna med SEM och AFM och testas med VNA. Analys och beräkningar utförs främst med programvaran Matlab och Gwyddion. Den föreslagna tekniken förbättrar provernas släthet med 78.95%, och Q-faktorn testas och visar en förbättring med 20.87% med hjälp av VNA.

Resultaten visar att det intermediära lagret med doppbeläggningstekniken signifikant förbättrar prestandan hos passiva RF-enheter genom att minska ojämheten på resonatorernas yta. Dessa resultat öppnar upp nya möjligheter för design och utveckling av högpresterande passiva RF-enheter inom olika tillämpningsområden, inklusive trådlösa kommunikationsystem, radarsystem och satellitkommunikation. Ytterligare studier kan genomföras för att minska defekter under tillverkningen och stabilisera prestandan hos silverbeläggningen.

Keywords: Keramisk beläggning, Dip-beläggning, Radiofrekvens, Passiva RF-enheter, Kvalitetsfaktor
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\newacronym{KTH}{KTH Royal Institute of Technology} \newacronym[shortplural={AFM}, longplural={Atomic Force Microscope}]{AFM}{AFM}{Atomic Force Microscope} \newacronym[shortplural={APTES}, longplural={(3-Aminopropyl)trithoxysilane}]{APTES}{APTES}{(3-Aminopropyl)trithoxysilane} \newacronym[shortplural={BW}, longplural={bandwidth}]{BW}{BW}{bandwidth} \newacronym[shortplural={kHz}, longplural={kilohertz}]{kHz}{kHz}{kilohertz} \newacronym[shortplural={GHz}, longplural={Gigahertz}]{GHz}{GHz}{Gigahertz} \newacronym[shortplural={InLens}, longplural={Immersion Lens Scanning of SEM}]{InLens}{InLens}{Immersion Lens Scanning of SEM} \newacronym[shortplural={IPA}, longplural={Isopropanol}]{IPA}{IPA}{Isopropanol} \newacronym[shortplural={MHz}, longplural={Megahertz}]{MHz}{MHz}{Megahertz} \newacronym[shortplural={Q-factor}, longplural={Quality factor}]{Q-factor}{Q-factor}{Quality factor} \newacronym[shortplural={RF}, longplural={Radio Frequency}]{RF}{RF}{Radio Frequency} \newacronym[shortplural={SEM}, longplural={Electron Microscope}]{SEM}{SEM}{Electron Microscope} \newacronym[shortplural={SE2}, longplural={Secondary Electron Scanning of SEM}]{SE2}{SE2}{Secondary Electron Scanning of SEM} \newacronym[shortplural={SMA}, longplural={SubMiniature version A}]{SMA}{SMA}{SubMiniature version A} \newacronym[shortplural={UV}, longplural={Ultraviolet}]{UV}{UV}{Ultraviolet} \newacronym[shortplural={VNA}, longplural={Vector Network Analysis}]{VNA}{VNA}{Vector Network Analysis} \newacronym[shortplural={ESB}, longplural={Energy Selective Backscattered-detector}]{ESB}{ESB}{Energy Selective Backscattered-detector} \newacronym[shortplural={FWHM}, longplural={Full Width at Half Maximum}]{FWHM}{FWHM}{Full Width at Half Maximum}