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Nanometric metal-film thickness measurement based on a planar spiral coils stack

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Abstract—This work presents a sensor composed of a differential arrangement of coils capable of measuring nanometric metallic film thickness. Experimental results achieved aluminium thickness measurements as low as 20 nm with a sensitivity of 3.8 mV/nm. This makes this sensor a flexible, nondestructive and cheap alternative for metallic thickness measurement down to nanometric scale.

Index Terms— Eddy current, electromagnetic sensor, metal-film thickness, planar inductor, spiral inductor.

I. INTRODUCTION

METAL-FILM thickness measurements have increased their importance due to the impact on physical, electrical, magnetic and mechanical properties of industry devices and the applications related to them like inspection of printed circuit boards [1], thin film electrodes [2], fatigue and quality inspection [3–7], control of the amount of material that is used [8] or nanoparticle fabrication [9] [10], where precised measurement of the film thickness is essential.

There are several methods used to measure the thickness of the added material, performing the measurement directly or indirectly from another property or variable measured from the sample. According to the management of the sample, these techniques can be classified as destructive and non-destructive techniques. Destructive techniques analyze only the samples that can be destroyed or from which can be extracted a piece to analyze, while the non-destructive can even be used in the production process or in final products without alterations on the sample piece.

The most widespread techniques are the optical methods which require a perpendicular cut from the sample to clearly observe the depth, using an instrument that allows the accurate observation of the sample by comparison with a reference. Thickness can be measured using optical instruments (e.g., microscopy), computational tools (e.g., deconvolution techniques), and mixed approaches (e.g., structured illumination) [11]. The main problems of this kind of techniques are the low-contrast image and the requirement of a proper powerful zoom that can achieve the correct resolution to observe clearly the measurement to be performed. Computational techniques could help to process the image by removing the blurred parts and enhancing the image itself, increasing the quality for all the post-processing to achieve the thickness measurement.

Some other techniques exploit the interaction with the surface of the sample, requiring a step to measure the height

and that way ensure the thickness measurement. This is the case of methods like scanning probe microscopy or profilometry. The problem with these techniques is that they are influenced by many external factors (i.e. roughness); besides they are invasive techniques as they require etching a window to measure the slope. It is worth mentioning that some improvements have been added to this technique as tools coming from the optical field like laser [12] or interferometric enhancements [13] [14], which reduce the external interferences but they still continue being invasive due to the necessity of the slope on the sample to measure the thickness.

On the other hand, among the nondestructive techniques, it can be found that some others exploit the electrical properties of the sample such as resistivity [15]. Such techniques use electrical current and the intrinsic resistivity of the deposited metal sample, relating the amount of material and its density, to perform the measurement; they use techniques like the Four-point microresistance probe method [16], that as a contact method extrapolates the thickness from the conductivity or surface resistivity of a test piece, obtaining a voltage difference between two of the four electrodes of a four-point probe, which means simplicity but lower accuracy, as it only achieves millimeter resolution [16].

In the optical methods, there can be found also nondestructive techniques that perform the metal-film thickness measurement in a challenging way assuming the metal film is as thin as to be considered “semitransparent”; this assumption implies that an appreciable amount of the light must reach the lower interface of the metal. Taking into account that metals are opaque, the only way to achieve that requirement is with really thin films, in the order of few tens or few hundreds of angstroms thick [17].

This is the case of ellipsometry, which measures the change in polarization, as light interacts with the sample, to determine film thickness but with the requirement that the metal film to be measured must be sufficiently thin to be partially transparent [18]. Furthermore this technique also requires the optical constants of the material to be analyzed, index of refraction (n), and extinction coefficient (k) [18] [19]. For the above mentioned reasons, ellipsometry will be always followed by a transmission technique in order to ensure the correct optical constants and thickness of a film.

Unfortunately, most metal films have optical constants that are not very different from each other, particularly in the visible region. Additionally the optical properties will vary with film thickness especially in films thinner than few

hundred nanometers. For the above mentioned, it is mandatory the determination of the properties by measuring different samples with different thickness to finally correlate and obtain the proper optical properties [17] [18].

An additional nondestructive optical technique is the Scanning White Light Interferometry, which again depends on the transparency of the sample as it uses the wave superposition principle. It uses the correlation algorithm with a high-resolution digital camera array to create a 3D representation that can be later processed to give the measurement with sub-nanometer accuracy comparable to spectroscopic ellipsometry [20]. The accuracy of the measurement is highly dependent on the efficiency of the algorithm used on the control of the scanning mechanism. Besides the transparent or semitransparent film must have a well-known refractive index or at least measurable index to perform the measurement [21].

Other nondestructive techniques use the power of different kinds of waves to penetrate the sample in order to analyze its internal structure, or simply analyze the changes on the incident wave and the way these variables are correlated with thickness. This is the case of ultrasonic, radiographic, and electromagnetic methods, which introduce electromagnetic or sound waves into the inspected sample in order to extract their properties.

Ultrasound method uses the velocity of ultrasonic waves that penetrate into the sample to measure the thickness, avoiding the dependence of optical and electrical properties. In this technique a pulse is transmitted through the sample. The frequency shift between the transmitted pulse and the received signal is used to estimate the thickness. There are also multiple echo wave techniques that improve accuracy analyzing timing between two successive back wall echoes that represent successive round trips of the sound wave through the test material. However, the problem on both techniques is that they depend on a specific ultrasound emitter- receiver and a highly signal-to-noise ratio to ensure the measurement [22]. These techniques also depend on the probe used, because as long as the frequency increases, the penetration is reduced optimizing resolution for thinner films, but making difficult the fabrication of that transducer. Furthermore the accuracy will be also related to the gauge of the probe.

There are other methods that measure the areal density and display the amount of added material as “thickness” like the quartz crystal oscillator microbalance, or the absorption of x-rays [23], electrons or beta rays [17]. These kinds of methods require the knowledge of the exact composition of the sample to ensure that the information analyzed is correct, as the ray penetrating the film is affected by the chemical composition of the sample. The depth resolution is limited by the signal-to-noise ratio and by the emission of the waves, especially the angle from which the data is acquired, plus having a wide dependence on specific expensive sources as in the case of X-ray scattering [24] [25]. Among these methods, techniques such as electron microscopy, scanning tunneling microscopy, ion beam scattering, or beta scattering can achieve high accuracy in a low level scale but, as mentioned before, the

dependence on highly specialized sources turns these techniques into quite expensive procedures plus the difficulty to perform measurements in situ or on the finished products.

One interesting application of these measurement methods of metal-film thickness is the quantification of conductive layers of plastic electronic devices. It is well known that to guarantee the flexibility of the substrate, the metallic pads and electrodes must be as thin as they can be. Nowadays, at these scales, the methods used to establish the thickness include SEM images [26] or resistivity measurements [27]; although these measurements need to be improve in quality and time in order to optimize the fabrication process as some authors mention [28].

Finally, there are techniques that use the electromagnetic induction effect, in which an alternating current applied to a conductive coil close to the metallic film to be measured. That current creates a primary alternating magnetic field and since a mutual inductance exists between the coil and the sample, circular eddy currents are generated in the sample. These currents will eventually create their own opposing electromagnetic field that will induce electromotive force (EMF) in the pick-up coil. The changes on that EMF will be translated to the desired measurement [29]. These sensors perform the measurement almost instantaneously and they are insensitive to dirt, humidity, oil or dielectric material making this technique ideal for in-situ measurements in industrial production.

One important thing to take into account in this technique is that the accuracy of the measurement system relies on the coil characteristics, such as shape and dimension of the coil, frequency of excitation source, as well as the distance between coil and sample. The literature describes different configurations of coils like planar spiral type [30] [31], toroidal type [32] [33], meander type [34] or solenoid type [35], and different alternatives for the sensor structure, like rounded tube inside the excitation coil [8], or between the excitation and compensation type [36]. As it can be seen this technique establishes a simple, low cost and robust method widely used for the industry due to its possibility of being easily fabricated [37] and inserted in the industrial chain of production [3].

In this paper, the application of a planar-spiral electromagnetic sensor with a reduced-offset for nanometric metal-film thickness measurement is discussed. In this paper is proposed the use of an electromagnetic sensor with a differential structure consisting in a planar excitation coil, a compensation coil to offer the null offset correction and a pick-up coil centered between the above mentioned coils. The proposed configuration [37], along with the design aspects and the application configurations are explained in detail.

This paper is organized in: Section II shows the sensor structure and set up configuration, Section III shows the experimental results and finally Section IV shows the conclusions.

Fig. 1. (a) Schematic diagram of the eddy current sensor configuration (b) Photograph of the sensor fabricated with PCB technology.

B : Magnetic field generated by eddy currents. V_o : Output voltage induced by the magnetic field B . *Comp C.*: Compensation coil. *Exct C.*: Excitation coil. *Pick-up C.*: Acquisition coil. I : current intensity applied to *Comp C.* and *Exct. C.*

II. SENSOR STRUCTURE AND SETUP CONFIGURATION

The sensor was designed with three spiral planar coils of 10 turns, which have copper conductors of $18\ \mu\text{m}$ thickness, $200\ \mu\text{m}$ width and a spacing of $300\ \mu\text{m}$, placed on FR4 substrate of $1.5\ \text{mm}$. The coils have a square shape with an external side of $10.3\ \text{mm}$. Printed Circuit Board Technology (PCB) was used to fabricate these planar coils. The distribution of the coils and the sensor can be seen in Fig. 1.

The sensor has a differential distribution where the pick-up coil (*Pick-up C.*) is placed between the excitation (*Exct C.*) and the compensation (*Comp C.*) coils at $2\ \text{mm}$ from each other. The distance between inductors affects the parasitic capacitances and, most important, the sensitivity of the sensor. This is the reason why we studied experimentally the dependence of sensitivity on coil separation (data not shown). It was obtained that the larger the distance the smaller the output signal for low frequencies. This was the reason to choose $2\ \text{mm}$, the smallest separation for this set up. This separation was obtained by means of plastic screws and screw nuts that can be used to change the distances among the elements of the sensor, improving the manipulation and

flexibility of the device. The differential arrangement is used to produce magnetic fields in opposite directions in *Comp C.* and *Exct C.*, in order to balance the induced voltage and creating as a result a theoretical zero-offset and practical reduced-offset sensor [37]. In order to calculate the mutual inductance between coils, we combined the image and Hoer methods [38], obtaining the value of $199,38\ \text{nH}$ and $301,58\ \text{nH}$ for the mutual inductance between exciting coils and between exciting and pick up coil respectively.

Additional advantages come from the compensation coil as it is capable of reducing the temperature influence on the pick-up coil. Actually it can correct any undesired effect coming from the sample, reducing the common-noise and increasing the sensitivity.

It is important to highlight that as the normal component of the field is the variable to be measured, the coils must be perfectly aligned, to guarantee a high sensitivity. Another important thing to take into account is the lift-off, which is the space between the sample and the pick-up coil, which can change the impedance [29]. Fig. 2. shows the output voltage as a function of the lift-off distance for an Al layer of $100\ \text{nm}$, applied current of $50\ \text{mA}$ and frequency $20\ \text{MHz}$. The shape of the curve is related with the decreasing of the created magnetic field. That is the reason why it is really important to control that distance. For the experiment $0.2\ \text{mm}$ was selected due the large output value; it was controlled by a glass slide of $0.2\ \text{mm}$ -thick. For more information about the design calculations and simulations of the sensor working principle used in this article, refer to [37].

The system works with a sinusoidal current applied to the excitation and compensation coils, with equal amplitude and frequency but 180° out of phase. It is created by a generator (33250A, Agilent) that is followed by a $100\ \Omega$ SMD resistor connected directly in series to the excitation and compensation coils of the sensor. The $100\ \Omega$ SMD resistor is used to assess the excitation current flowing through the sensor coils. Then, the amplitude of the output voltage is measured on the pick-up coil, which is used to assess the thickness by means of a calibration pattern established previously without sample. It is performed by an oscilloscope (TPS2024, Tektronix) connected by a serial RS232-USB cable (DS_US232R-10, FTDI Ltd.) to

Fig. 2. Measured output voltage (V_{opp}) of the sensor increasing the lift-off distance, for a sample with $100\ \text{nm}$ of Aluminium. The frequency was set at $20\ \text{MHz}$ applying an excitation current of $50\ \text{mA}$.

a computer running a Virtual Instrument (Labview 8.6) programmed to configure the equipment easily and which automatically performs the measurements.

The signal generator is also connected to the computer using a GPIB-USB cable (KUSB-488, Keithley). A home-made program calculates the nominal signal that must be applied by the generator, taking into account the frequency, the sensor parameters and the desired excitation current. It is established a control loop to modify the amplitude and frequency of the signal to achieve the desired values with a

Fig. 3. Block diagram of the readout electronic. V_e : Excitation voltage. Osc : Oscilloscope. R_{sh} : Shunt resistor. Each coil was modeled by its electrical parameters (L , C , R) and the sample is modeled by L_s of the electromagnetic interaction with the coils and R_s resistivity of the material.

suitable range of error. Then, when these variables are controlled, it establishes the sensor behavior without sample and then the setup is ready. A block diagram of the readout electronic is shown in Fig. 3.

Samples to test the sensor were made on silicon wafers of 4 inches diameter with $\langle 100 \rangle$ structure, p-doping, with a conductivity of 4 - 40 $\Omega\text{-cm}$ and 500 μm of thickness. It was added an extra 0.1 μm SiO_2 film to improve the metal adhesion. Then, aluminium was added by sputtering technique creating nominal thickness of 20 nm, 30 nm, 40 nm, 50 nm, 60 nm, 70 nm, 80 nm, 90 nm, 100 nm, 150 nm, 200 nm, 300 nm, 400 nm, 500 nm, 1 μm , 2 μm and 4 μm . Finally the wafers were cut into square chips of 10 mm side to adapt it to the dimensions of the coils.

In order to determine the accurate deposited thickness of the metallic films, two chips of each wafer were selected. Initially, a drop of positive photoresist (HIPR 6512, Fujifilm) was added on each chip. The photoresist was baked 1h at 100°C. Then, the metallic films were engraved until a step using an etch solution (Defreckling Aluminium Etch-DAE, Fujifilm) was created. The work temperature was 45°C and the DAE speed of engraving was 200 nm/min. The height of the step engraved in each chip was measured using a surface profiler (Dektak 150, Bruker). Finally, the metal thickness was determined doing an average of the step engraved for both chips of each wafer.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed electromagnetic sensor was tested with 19 chips of different aluminium thickness, including a chip without aluminium film. Subsequently, to determine the thickness, a circular glass film of 10 mm of diameter and 0.2 mm of thickness was used to separate the chips from the sensor surface. The performance of the measurement system was configured to excite the sensor with a sinusoidal current of 12 mA, doing a frequency sweep from 1MHz to 80 MHz in steps

Fig. 4. Frequency response of the peak to peak output voltage (V_{opp}) measured for silicon-aluminium samples with different thickness, separated from the sensor by a 0.2 mm glass slide. The thicknesses of the aluminium films measured by profilometry are indicated as a reference.

of 1 MHz. The resonance frequency of the systems lies at 43 MHz and, in theory, around this value should be the best frequency to measure due to the larger output signal. However we measured in the range 1-20 MHz because at higher frequencies the influence of the parasitic capacitances between inductors provokes instabilities in the output of the sensor. Besides for frequencies above 20 MHz the response of the sensor is not linear and it complicates its calibration. The value of the magnetic field generated by the coils was obtained analytically using Biot-Savart law and by means of a Matlab® program specially designed for this purpose. As it was expected the magnetic field is proportional to the applied intensity current, obtaining the value of 37,15 μ T for 12 mA.

In all the measurements the amplitude and the frequency of the excitation current were controlled to have maximum errors of ± 0.1 mA and ± 10 kHz, respectively. The output voltage was computed as the result of an average of 128 measurements. The room temperature was in the range of 23 $\pm 2^\circ$ C during all the experimental tests. The peak to peak value of the induced voltage, in the pick-up coil (V_{opp}), at different frequencies is shown in Fig. 4.

As it can be observed in that figure, the shape of the frequency response is characteristic for each sample, confirming the dependence on the electromagnetic coupling between the sensor and the sample. The offset signal without the sample is due to asymmetries in the assembly of the sensor, which was controlled mechanically by screws and differences between the excitation coil and the compensation coil introduced by the fabrication process itself. It is important to highlight that the associated errors come also from the conditions used to measure, like the range of frequency. According to oscilloscope specifications, the relative error associated with the measurement of the frequency was 1.9 %. Fig. 4 also demonstrates that this sensor is accurate for the measurement of thin layers with thickness smaller than 200 nm.

In addition to the frequency, the excitation current is another important factor to take into account for the sensitivity of the sensor. The sensor response (V_{opp}) as a function of the amplitude of the excitation current was measured as well. The sensor frequency was set at 20 MHz and the excitation current was increased from 1mA to 50 mA in steps of 5 mA, keeping constant the space between the sample and the sensor. The relative error in the measurement of the current was 6 %. The measurements of the output voltage for 3 samples with different metallic thickness are shown in Fig. 5. They demonstrate that the output voltage of the sensor increases proportionally with the excitation current, accordingly with the electrical model of the system shown in [37]. These results offer an alternative way to deduce the thickness of the samples that can be related with the slope of the lines on Fig. 5, as it changes considerable for each thickness.

Fig. 4 showed that the proposed sensor detects the silicon substrate. In this case, eddy currents are originated mainly by majority carriers (i.e. holes) inside the p-type silicon sample. Taking into account this phenomenon and as a first approximation, the voltage measured for the silicon was

subtracted from the voltage measured for the samples having an aluminium layer, to quantify the output voltage induced by the aluminium layers, as it is shown in Fig. 6. It is important to highlight that the excitation current was raised to 51.6 mA to increase the sensor sensitivity during the test, in good agreement with the results shown in Fig. 5.

Fig. 5. Measured output voltage of the sensor increasing the excitation current, for 3 samples of different metallic thickness.

Fig. 6. Output voltage induced by the aluminium layers of the samples as a function of their metallic thickness, in a frequency range from 1 MHz to 20 MHz applying an excitation current of 51.6 mA.

Fig. 6. shows that the sensor output increases with the thickness of the aluminium film as expected from Fig. 4. These results also indicate that there is a thickness limit where the sensitivity has an abrupt reduction as the sensor enters into a saturation regime. This effect is caused by the non-uniform distribution of eddy currents through the entire volume of the sample. It is known that eddy currents density decreases exponentially with the distance from the surface, depending on the frequency, electrical conductivity, and magnetic permeability [39]. The reduction of the saturation thickness is caused by a decrease of the penetration of eddy currents in the metal film along with the frequency. Below the saturation zone the dependency of the sensor response with the metal thickness can be observed. The lack of linearity in the

approximation of saturation is caused by the growing influence of the parasitic capacitances associated to the experimental setup and the sensor itself. Another important element to notice is that the sensitivity of the sensor improves with the frequency, reaching a maximum of 3.8 mV/nm for 20 MHz in the range of 20-70 nm. This value is higher than sensitivity ratios found on literature, showing the potential of the proposed sensor to measure thickness of metallic films in the range of nanometers [8] [40]. On the contrary, when the frequency is decreased the sensor is able to measure thickness of several microns: this way, for 1 MHz the output voltage is not saturated up to 3.5 microns, showing a sensitivity of 0.01 mV/nm, suitable for these values of thickness. Therefore the choice of the frequency is the main parameter to change the range of the thickness measurement.

Finally, a test was carried out to estimate the stability and the resolution of the design setup. An excitation current of 50 mA at a frequency of 20 MHz was applied to the sensing device. The rest of the conditions used in the previous test were maintained to perform the current experiment. Fig. 6 shows the results demonstrating that, even though the measurement was performed with standard equipment that did not balance the residual offset of the misalignments in the coils, the detection limit goes down to 20 nm.

Fig. 7. Response time of the sensor evaluating the stability with an aluminium sample and without it at 20 MHz.

Additionally, as it can be seen in Fig. 7, there were observed instabilities in the order of 1.2 % of the measured voltage, confirming a resolution of 3.8 mV/nm in the proposed system.

Finally, although the configuration of the proposed sensor gives a great performance in the nanometric scale, it is important to notice that improving the fabrication process of the sensor, the coupling between the coils and using a specifically designed electronics to measure will improve the resolution and sensitivity.

IV. CONCLUSIONS

A differential electromagnetic sensor based on spiral planar coils for metal film thickness measurement has been presented and analyzed. The sensor response was evaluated experimentally, determining its dependence on the amplitude and the frequency of the excitation signal. It was found that frequency conditions the penetration depth of eddy currents in the metallic film, as well as the sensitivity of the sensor to different thickness. Experimental measurements show a sensitivity increase with the amplitude of the excitation current, in good agreement with the expected results.

Moreover, it is important to highlight that the output voltage is highly dependent on the sample characteristics such as conductivity, magnetic permeability, and others. Thus, it is important to create a calibration curve, specific for each material in order to ensure the accuracy of the measurement. Besides, it is important to avoid two phenomena that could reduce the accuracy of the sensor response: the lack of linearity originated by the parasitic capacitance associated with the system and the saturation regime related to samples thicker than 1000 nm, which limits the output voltage for thickness measurement at high frequencies.

The maximum sensitivity of this sensor was found in the range of 20 nm to 200 nm at 20 MHz, turning it into an adequate alternative for thickness measurements in nanometer scale. This sensor also acts as a low cost alternative due the ease of the fabrication and the fact that it does not depend on any specialized software or expensive measurement equipment, and it does not require any iterative process like ellipsometry.

Advantages mentioned previously set the proposed sensor as a quick, easy, flexible, cheap and nondestructive tool for nanometric metal-film thickness measurement, even performed in in-situ process of many fabricated products.

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