Microwave Characterization of Nickel

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Abstract— In recent years, nickel has found new applications in RF microfabricated filters and MEMS switches, as it is proving to be a convenient structural material and suitable for realizing power-efficient electrothermal buckle-beam microactuators. While nickel is becoming a material of choice for processing engineers, there is a serious issue of RF characterization at microwave frequencies. This paper investigates some of the issues associated with both measurement and modelling of nickel. It has been found that RF engineers are currently faced with the problem that there is insufficient data available to undertake simulation designs with a high level of confidence at microwave frequencies.

1. INTRODUCTION

Nickel has for many decades been used for realizing ferrites, employed in radio frequency (RF) applications, due to its high magnetic permeability at low frequencies. However, in recent years, electroplated nickel has been used as a structural material in RF microfabricated circuits [1] and even radio frequency microelectromechanical systems (RF MEMS [2]) applications [3–5]. With the former, at around 30 GHz, weakly magnetized nickel has twice the surface resistance of silver or copper, but is chemically and mechanically more robust [1]. Moreover, it has a relatively small deleterious effect [1]. Also, when used in electrothermal buckle-beam microactuators, since nickel's thermal expansion coefficient is approximately five times greater than that of polysilicon, the same displacements can be obtained at a much lower temperatures [5]. Therefore, its use in RF transmission lines and microactuators permits co-fabrication, having the same lithographic steps [5]. On the other hand, creep and high-cycle fatigue of nickel structures, particularly at elevated temperatures, may still limit their use in electrothermal microactuators for some applications, due to the impact on their reliability and lifetime [5].

It is very important for the RF designer to understand and know the frequency characteristics of all the materials to be employed in the development of a future device, circuit or system. Surprisingly, very little has been reported on the magnetic permeability of nickel. A survey of textbook values is given in Table 1, along with additional data from a leading commercial 3D electromagnetic simulation software package: Ansoft's High Frequency Structure Simulator (HFSS$^{\mathrm{TM}}$).

Table 1: Textbook survey of dc bulk conductivity and magnetic relative permeability.

Reference	σ_o [S/m] $\times 10^{-7}$	μ_r
Brown et al. [1]	1.4	1
Olver [6]	1.15	50
Carter [7]	1.28	600
Popovic and Popovic [8]	1.28	600
HFSS$^{\mathrm{TM}}$ [9]	1.45	600

Clearly, within Table 1, very little consensus exists on the combined values of dc bulk conductivity and magnetic relative permeability. Indeed, with the latter, no information is given as to whether the values represent dc values. Also there is no information on how the nickel was deposited or its level of purity. This makes the design of nickel structures for microwave applications very difficult indeed. This paper tries to address the issue of characterizing the frequency dispersive nature of magnetic permeability for nickel.

2. GENERAL FREQUENCY BEHAVIOUR

When an alternating magnetic field is applied, at low frequencies, the magnetic domains respond to it and produce a high permeability material. This works up to hundreds of megahertz with insulating ferrites but only up to a few kilohertz for conducting ferromagnets like nickel. The initial permeability is measured with almost no externally applied magnetic field, where the domain walls are just beginning to move from their equilibrium state. The present investigation is concerned with the measurement of the initial permeability in small magnetic fields, where all boundary movements are reversible. At low frequencies the permeability is high, because the domains can follow the applied field. As frequency increases, movement of the domains lag behind the applied field and the resulting increase in loss, caused by friction, is represented by the associated increase in the imaginary part of initial permeability. At infrared frequencies and shorter wavelengths, the domains cannot follow the applied field and so there is no loss from trying to follow it and the relative initial permeability approaches unity. Therefore, the dc value of initial permeability must fall off as frequency increases and the greatest frequency dispersion generally occurs between 0.1 and 10 GHz; the decrease in permeability for nickel is in the neighbourhood of 1 GHz [10].

3. SURVEY OF MEASURED MICROWAVE DATA

Scientists have been investigating the properties of magnetic materials for a century. In 1951, Bozorth collated all the data that was available during that time for the frequency dispersion characteristics of permeability. The collated graphs are reproduced in Fig. 1 [10].

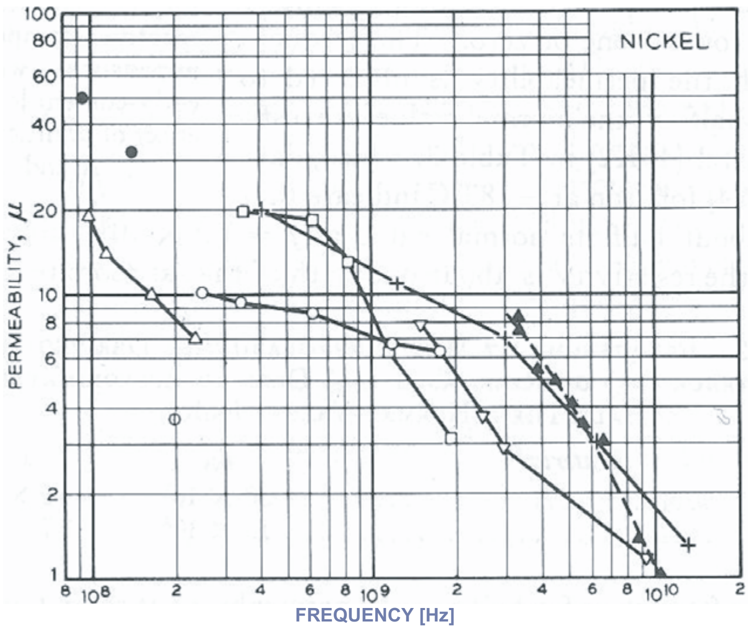

Figure 1: Measured frequency characteristics of initial permeability for nickel [10].
(+ Arkadiew [11], ∇ Simon [12], ▲ Hodsman et al. [13])

From Fig. 1, it can be seen that the frequency behaviour does indeed show a low frequency value that drops off at around 1 GHz. However, at any one frequency, the results from different researchers give large discrepancies in their measured values. Surface conditions are thought to be an important factor at microwave frequencies. For example, a thin oxide film, formed on the metal during heat treatment, may cause the apparent permeability to decrease by a factor of 10 [10]. Moreover, Arkadiew also noted an increase of high-frequency permeability when magnetic material is annealed [11].

This inconsistency in measurement data makes the characterization of nickel very difficult. The following reviews some of the experimental approaches undertaken and highlights key findings.

3.1. Arkadiew [11]

Back in 1919, reflectivity measurements were performed by Arkadiew with fine wire gratings made from ferromagnetic materials. Here, initial permeability was shown to decrease from 20 at 0.41 GHz down to approximately 1.2 at 12.3 GHz [11]. Unfortunately, the reflection coefficients from ferromagnetic and non-ferromagnetic metals, having medium to high conductivities, for both plane and guided waves, do not differ sufficiently to allow direct measurement [13].

3.2. Hodsman et al. [13]

In 1948, measurements are carried out by comparing the attenuation constants of 1.4 m length coaxial transmission lines having an inner conductor made from 99.5% purity nickel and reference nonferromagnetic (e.g., constantan or German silver) wire. Here, the attenuation constants are derived from circles on an impedance Smith chart, which were produced by measuring the standing-wave patterns in the transmission line for different positions of a movable short circuit that were then transformed into values of input impedances. The results are given in Table 2. Calculations showed that the probable error in the recorded values for permeability is of the order of 15% for nickel.

Table 2: Measured initial permeability [13].

Frequency [GHz]	dc	3.356	3.374	3.956	4.545	5.062	5.564	6.522	8.772	9.615	10.084
Initial Permeability	17	8.3	7.5	5.6	5.0	4.1	3.4	3.0	1.5	1.03	1.0

3.3. Hsu et al. [14]

Hsu et al. recently attempted to model the 20 to 40 GHz frequency band power loss behaviour of 8, 10 and 16 mm length nickel CPW transmission lines [14]. A high-resistivity silicon (HRS) substrate was employed that also has a 300 nm layer of thermally grown silicon dioxide. The nickel lines are deposited by electroplating a low-stress 2 µm thick nickel layer on top of a thin Ti/Ni (80/50 nm) seed layer. The feed lines were made from gold, using a low-stress RF sputtering process. Parameter extraction techniques were then used to determine values of relative initial permeability within a 20 to 40 GHz frequency range of interest.

While this may at first appear to be a valid approach, on closer inspection there are a number of issues. For example, on the experimental side, bond-wires or air bridges were not introduced at the launch discontinuities or at regular intervals along the line in order to suppress unwanted slot-line modes. Also, it can be assumed that the RF on-wafer measurement samples were tested directly on a metal wafer chuck. As a result, while the lowest-order TM mode can be calculated to be approximately 61 GHz, for an ideal lossless 500 µm thick silicon wafer [15], the onset into this mode will be seen at much lower frequencies, due to the dramatic reduction in the resistivity of the HRS silicon wafers ρ_s caused by the high temperatures involved in the growth of the silicon oxide layer. In theory, the dielectric constant of the HRS ε_{rs} will also change. Finally, no mention was made of the level of nickel oxidation immediately prior to measurement.

4. MODELLING STRATEGIES

4.1. Relaxation-effect Models

The speed at which the boundary movements can follow a high frequency alternating field must ultimately depend on the speed at which the spin rotations can be accomplished. As the period of the applied magnetic field approaches the relaxation time of the spin rotations, the boundary movements lag further behind the applied field and the apparent permeability would decrease to unity.

Frequency dispersion of initial permeability, μ, for ferromagnetic materials was first proposed by Becker with the following overly simplified model [16]:

$$\mu(\omega) = \frac{\mu(0)}{1 + j(\omega/\omega_c)} \quad \text{and} \quad \mu(\omega) \equiv \mu(\omega)' - j\mu(\omega)'' \equiv (1 + \chi_m(\omega)) \tag{1}$$

where $\mu(0)$ = initial permeability at dc and ω_c = critical frequency, which is a function of the domain length and dc characteristics of the material [13]. For nickel, a very approximate fit can be obtained with $f_c = \omega_c/2\pi \sim 0.5 - 1.6$ GHz, indicating a domain length of ~ 4 µm [13].

This rather crude model can be improved upon by using the following well-known Drude model for magnetic susceptibility, $\chi_m(\omega)$:

$$\chi_m(\omega) = \frac{\chi_m(0)}{1 - (\omega/\omega_o)^2 + j\omega\tau} \quad \text{where} \quad \tau = \frac{1}{\omega_o^2 \tau_o} \quad \text{and} \quad \chi_m(\omega) \equiv \chi_m(\omega)' - j\chi_m(\omega)'' \tag{2}$$

where $\chi_m(0)$ = static magnetic susceptibility, ω_o = resonance frequency and τ_o = characteristic damping time.

4.2. Parameter Extraction Techniques

Hsu et al. adopted a brute-force approach to characterizing the relative initial permeability, μ_r, of nickel. First, a value for dc bulk conductivity of $\sigma_o = 7.99 \times 10^6$ S/m was extracted from over-simplified multimeter measurements of line resistance. It should be noted that this value is considerably lower than those quoted in Table 1. If one employs the standard 4-point probe test approach then a more accurate value for dc bulk conductivity can be determined. The authors expected a value of 14.5×10^6 S/m, which represents an 81% increase in value. This could potential cause a source of error. The attenuation constant of a CPW line, due to conductor loss, is directly proportional to surface impedance and this, in turn, is directly proportional to $\sqrt{\mu_r/\sigma_o}$. Therefore, any error in their extracted value of conductivity could be translated directly to their value of relative initial permeability.

Second, a loss tangent value of $\tan\delta = 10 \times 10^{-4}$ for the HRS was extracted by modelling a 15 mm length non-ferromagnetic (i.e., gold) CPW line using HFSS™. Using the measured value of σ_o for the nickel and the extracted value $\tan\delta$ for the HRS, Hsu et al. extracted a frequency-independent value of $\mu_r = 1.7$ for the relative initial permeability of nickel.

It is well known that HFSS™ can produce results that do not conform to measurements, due to problems when assigned boundary conditions, wave port dimensions, solve functions, solution frequencies, convergence targets, etc. [17]. As a result, by entering wrong values of ρ_s, ε_{rs}, σ_o and μ_r it is possible to force simulation results to exactly match measurements within narrow bandwidths, especially when transmission phase angle is not considered.

Hsu et al. also performed analytical calculations of attenuation constant due to conductor loss, based on the work of Holloway et al. [18]. Using this alternative method, Hsu et al. determined another frequency independent value of $\mu_r = 2.1$ for the relative permeability of nickel.

On closer inspection, both the simulated and calculated frequency responses only manage to cut across the measured frequency responses, within the 20 to 40 GHz frequency range of interest. In other words, exact fits only occur at a single frequency, and this frequency changes with length of transmission line. It can, therefore, be concluded that the extraction technique as described and the resulting values for relative permeability cannot be considered accurate, even though these values are close to the expected value of unity.

5. CONCLUSIONS

Frequency dispersion characteristics of magnetic permeability for nickel have been investigated, from the issues of measurement and modelling. It has been found that RF engineers are currently faced with the problem that there is insufficient data available to undertake simulation designs with a high level of confidence at microwave frequencies. While some experimental data exists for the real part of the relative initial permeability, there is still considerable uncertainly as to how this relates to the deposition process, material purity and level of oxidation. Moreover, to the best of the author's knowledge, no measured data exists for the imaginary part of permeability. The well-known Drude model is expected to be able to give an empirical fit to future experimental data. In addition, extraction techniques using 3D electromagnetic modelling software may offer another way forward. Here, both the magnitude and phase angle of the transmission characteristics for impedance-matched transmission lines must be considered, in order to be able to produce frequency-dependent complex values of permeability at microwave frequencies.

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