Rivier's experimental values [2]. By comparing the curves, our formulas are found to agree well with Rivier's experimental results.

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Resistivity of Thin Metal Films

H. K. CHAURASIA AND W. A. G. VOSS

***Abstract*—It is shown that the sheet resistance, and hence the resistivity, of very thin metal films (<100 Å) can be determined conveniently and accurately by microwave measurements. Accuracy is limited by VSWR measurement, film-holder design, and short-circuit quality. DC and microwave resistivity measurements are given for gold films on cleaved mica.**

I. Introduction

A waveguide impedance method due to Slater [1] for measuring the conductivity of metal films has been used by Clark [2]. This method is simpler than the field approach, which has been used for metal and semiconductor films on thick substrates [3]–[6], and provides a useful technique for determining the conductivity of ultrathin (<100 Å) metal films.

As the film thickness becomes comparable to the substrate surface irregularities, its macroconductivity is as much a function of the film structure as the microtopography of the substrate. Cleaved mica faces, the smoothest available, show topographic irregularities of the order of the lattice parameters [7]. These are at least seven orders of magnitude smaller than a wavelength at 10 GHz, and as such will not affect the wave.

A film of thickness $l \ll \delta$, the skin depth, and bulk conductivity σ, placed across a rectangular waveguide operating in the TE_{10} mode, create an admittance $\sigma l + Y_t$, where Y_t is the admittance of the waveguide termination at the film and is zero when a perfect short is placed at $z=0$ ($\lambda_g/4$ behind the film in Fig. 1). The conductance σl then corresponds to the conventional definition of the dc sheet resistance, i.e., $R_s = 1/\sigma l\ \Omega/\square$. The microwave value $R_s(\mu)$ can be measured as rZ_0 when $R_s(\mu) \geq Z_0$, or Z_0/r when $R_s(\mu) \leq Z_0$, where r is the VSWR and Z_0 is the wave impedance at the operating frequency. Replacing the film by a short circuit at $z = -\lambda_g/4$, any reactive part resulting from a significant discontinuity due to the substrate and its mounting in the waveguide will be indicated by a minima shift other than zero ($R_s(\mu) = Z_0/r$) or $\lambda_g/4(R_s(\mu) = rZ_0)$.

It can be shown that a thin, lossless dielectric sheet of thickness d and relative permittivity ϵ will cause a VSWR given by [8]

$$r_\epsilon = 1 + \frac{2\pi d}{\lambda}\left[\sqrt{\{\epsilon - (\lambda/\lambda_c)^2\}/\{1-(\lambda/\lambda_c)^2\}} - 1\right] \quad (1)$$

where λ and λ_c are the free-space and cutoff wavelengths, respectively.

The accuracy with which the resistivity $\rho_\mu = lR_s(\mu)$ can be determined thus depends on 1) making $l \ll \delta$; 2) $Y_t = 0$, demanding an ideal short circuit and lossless waveguide; 3) the accuracy of measuring r, particularly when $R_s(\mu)$ is much different from Z_0; and 4) the effects of the discontinuity caused by the substrate and film holder.

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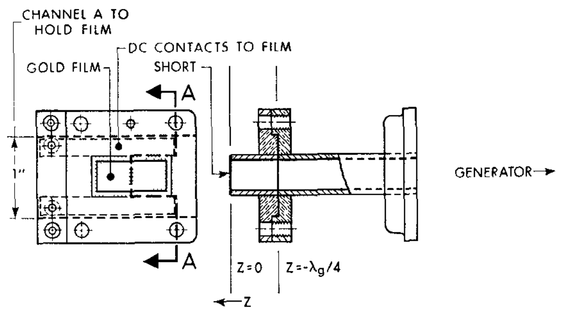

Fig. 1.

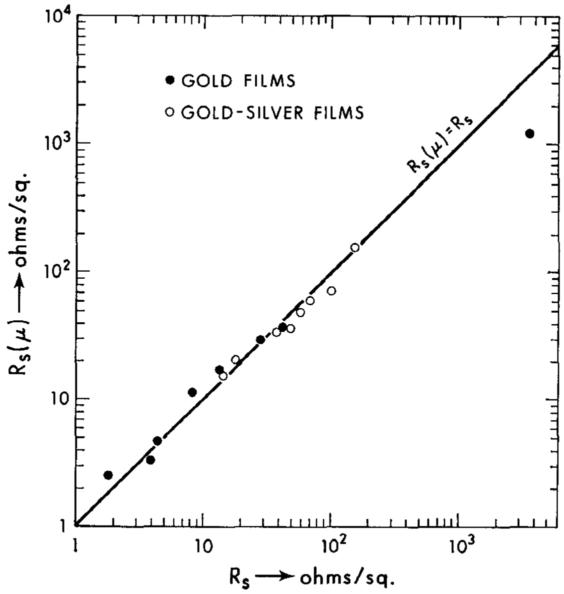

Fig. 2.

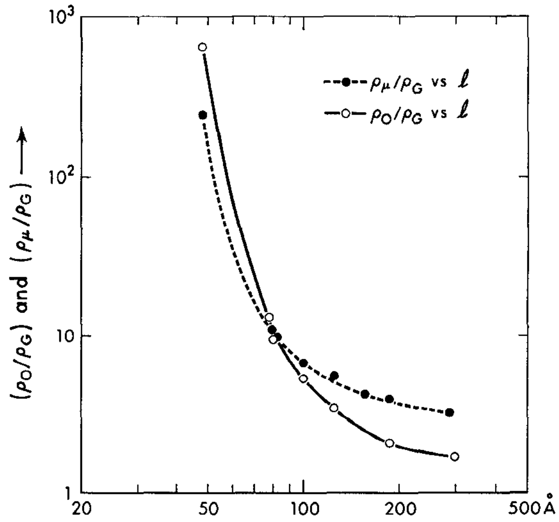

Fig. 3.

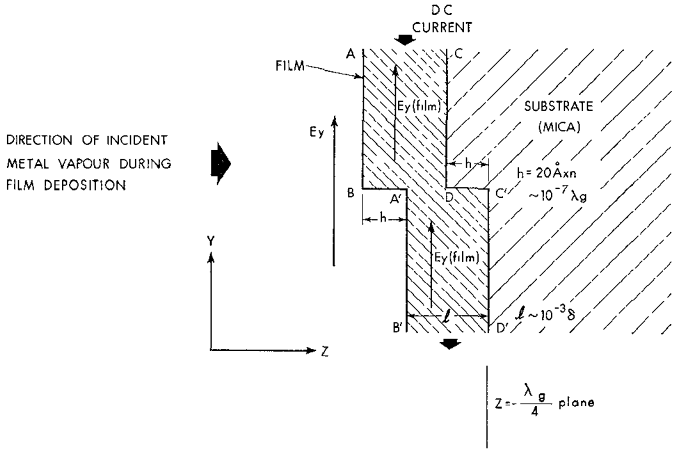

Fig. 4.

II. Experimental Results

Measurements were made at 9700 ± 2 MHz in X-band waveguide for which $Z_0 = 511.8\Omega$ for gold and gold–silver films deposited by high-vacuum evaporation on air-cleaved mica sheets with $d \leq 0.03$ mm and mounted as shown in Fig. 1 [9]. The film dimensions between the silver contact strips were 1 by 1/2 in, giving two squares in parallel. Thus twice the dc resistance (measured to within ± 1-percent accuracy) gives R_s. In practice, even with a mica sheet on both sides of the film, there is sufficient capacitive coupling between the contact strips and the broadside waveguide walls for the film to act essentially as a conductance across the waveguide [10].

The discontinuity was assessed using the sliding load technique [11]. The VSWR of the holder without a mica sheet was 1.035 (corresponding to a reflection coefficient $|\Gamma_1| = 0.017$). With a 0.03-mm thick mica sheet, the VSWR increased to 1.056 ($|\Gamma_2| = 0.027$). Considering Γ_1 and Γ_2 in phase, $\Gamma_e = 0.01$ and $r_e = 1.02$, which closely agrees with the value 1.0124 calculated from (1). The maximum error, at $R_s(\mu) = Z_0$, is then found to be ± 2 percent if r_e is ignored. As the VSWR can be measured to within 2 percent for $r \lesssim 10$, the total error is less than ± 5 percent for $50 \leq R_s(\mu) < 5000\ \Omega/\Box$.

The measured values of $R_s(\mu)$, R_s, ρ_μ, and dc resistivity $\rho_0 (= lR_s)$, the last two normalized to the bulk resistivity of gold ($\rho_G = 2.44 \times 10^{-6}\ \Omega \cdot \text{cm}$), are shown in Fig. 2 and 3.

III. Discussion

No direct correlation between R_s and $R_s(\mu)$ has been found. Fig. 2 suggests that for R_s below about 40 $\Omega/\Box$, $R_s(\mu)$ is generally greater than R_s; there are some points where $R_s(\mu) \simeq R_s$; otherwise, $R_s(\mu)$ is generally smaller than R_s. These factors are further emphasized in Fig. 3 where a transition from $\rho_0/\rho_G < \rho_\mu/\rho_G$ to $\rho_0/\rho_G > \rho_\mu/\rho_G$ is seen to occur for l around 80 Å. At 50 Å, ρ_0/ρ_G is about three times larger than ρ_μ/ρ_G, a difference far beyond the limits of experimental error.

Waveguide losses and an imperfect short circuit are likely to reduce the measured value of r. Thus when $R_s(\mu) = rZ_0$, $R_s(\mu)$ will be smaller than R_s; for the case when $R_s(\mu) = Z_0/r$, $R_s(\mu)$ will be larger than R_s. For the former case, however, l is less than about 80 Å and a much more important factor is the surface microtopography of the substrate. Carefully cleaved mica sheets, although atomically smooth over large areas, still exhibit a hill-and-valley topography, and cleavage-step heights h are known to be $\sim$20 Å or integral multiples thereof [7]. Fig. 4 shows an idealized cross section of a film with l slightly larger than h and no deposition on the step. The resulting constricted area through $A'D$ forms a higher resistivity path for dc, and a multiplicity of such defects would considerably increase the measured R_s value. E_y, however, is essentially the same at faces AB and $A'B'$ since $h \sim 10^{-7}\ \lambda_g$. Also, E_y (film) and the resulting film current density σE_y (film) are uniform over l, since $l \leq 10^{-3}\ \delta$. Surface undulations further lengthen the dc path. At microwave frequencies, on the other hand, Ament [12] has shown that an approximate value of the reflection coefficient of a perfect conductor with statistically distributed surface irregularities is $\exp(-2k^2\overline{h^2}\sin^2\theta)$, where $k^2 = \omega^2\mu_0\epsilon_0$, $\overline{h^2}$ is the mean-square height of the irregularities, and θ is the angle of incidence of the wave. This is almost unity for $\overline{h^2} \ll \lambda^2$. The result of microscopic surface irregularities on $R_s(\mu)$ measurements must therefore be minimal. The dc resistivity calculated using macroscopic film geometry is meaningless as l approaches h or $(\overline{h^2})^{1/2}$, particularly because no two cleavage faces will be the same.

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Compact YIG Bandpass Filter with Finite-Pole Frequencies for Applications in Microwave Integrated Circuits

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***Abstract*—A miniaturized, narrow-bandwidth, two-stage YIG bandpass filter is described that can be incorporated into microstrip circuits. The selectivity is increased by introducing finite-pole frequencies. This is realized by additional coupling between the input and output lines leading to the YIG-coupling section.**

The problem of achieving high selectivity in microwave integrated circuits (MIC's) has not really been solved for reasons that microstrip is too lossy, dielectric resonators are temperature sensitive, and cavity resonators are too large. This short paper describes a fixed, tuned, YIG bandpass filter with permanent magnets that satisfies the conditions required for narrow-bandwidth filters in MIC's: small size, tolerable losses, and temperature stability.

Although single-crystal YIG sphere resonators [1][1] with typical diameters between 0.3 and 1 mm are compatible in size with microstrip lines that have a substrate thickness and stripline width of the same order, a hybrid integration of the YIG filter into the MIC was preferred to a full integration of the YIG sphere resonators into the microstrip substrate. There are several reasons that lead to the preference of a hybrid integration: 1) the biasing magnet, which in any case must be built around the YIG filter; 2) difficulties in realizing a planar coupling structure for YIG bandpass filters in only one plane, as given by the circuit plane of the substrate; and 3) the adjustments and tests of the YIG filter are more easily made in a test jig than in a more or less complex microwave circuit.

Therefore, the YIG filter was designed as a separate miniaturized component which, like a transistor or a diode, can be built into the appropriate part of the MIC. Fig. 1 shows the miniaturized YIG filter as a separate component and the YIG filter component connected to a microstrip substrate (seen from the ground plane side and from the circuit side of the substrate). An area of only 8×5 mm^2 is needed on the circuit plane of the substrate for mounting and connecting the filter. The filter is a two-stage type consisting of two orthogonal semiloop coupling structures; the permanent magnet sys-

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[1] In [1], the general properties of YIG resonators are described.