# A Study of Microwave Behavior of a Thin-Print Gold Ink

By

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*A newly developed suspension of nanometer size gold particles is utilized to design a thin-print etchable gold paste. The new paste is suitable for screen printing on ordinary 96% alumina substrates and provides an ultra thin, but very dense, fired film. The thinness of the film results in substantial cost savings, while at the same time allowing for the fabrication of very narrow lines. Very high fired film densities and smooth surface finishes result in excellent performance at microwave frequencies. Transmission characteristics at frequencies up to 4 GHz compare favorably to sputtered thin film gold and copper. Characterization at higher frequencies is underway.*

Key Words: Nanometer Particles, Etching, Thin Print, High Frequency, Microwave

**Introduction**

The availability of higher bandwidth devices, coupled with the need for faster signal propagation and smaller and denser electronic circuitry, have intensified interest in dielectrics with lower constants[1-2] and more advanced metallization technologies. The metal must offer environmental reliability, cost effectiveness, and the ability to form narrow lines with good high frequency performance.

Photolithographic techniques have been used extensively on deposited gold films to form electronic circuits. Thin film deposition is the oldest and most widely used method of producing high reliability RF and microwave circuits. Thick film metallo-organic inks have also been screen printed and fired on glazed or polished alumina substrate to form a thin gold layer. For high volume applications, this provides an overall lower manufacturing cost than MOCVD and other thin film techniques. The substrate cost remains an issue, as the surface finish must still be quite smooth.

Advances in the development of relatively small, spherical, mono-size gold particles have enabled the use of standard suspension pastes to produce dense fired films of 4-8 µm thick. At these thicknesses the substrate surface finish is no longer an issue and good microwave behavior of such films, fired on 96% alumina, have been reported. Improvements on two aspects of this technology may, however, result in its more widespread use. First, because photo-lithography is a subtractive technique, thick deposits result in a high level of waste in the form of etched away gold. Second, with thicker deposits, undercutting presents a challenge during etching of narrow lines. This paper will describe a newly designed thick film paste, KOARTAN 4550, based on nanometer size gold particles. This technology offers the ease and cost competitiveness of printing and etching on 96% alumina substrate, much thinner prints, and competitive high frequency performance.

## Materials Technologies

Traditionally, gold powders for thick film paste have either been manufactured by aqueous chemical precipitation or by an aerosol method, such as spray pyrolysis. Depending on the chemistry used, the wet precipitation method can produce amorphous, flake, flake/sphere, or spherical powders. The aerosol method generally yields spherical powders with very tight particle size distribution and microscopically smooth surfaces. The tight PSD and smooth surface provide a significant advantage in packing and fired densities, resulting in good conductivity and high frequency transmission. This type of powder, however, is substantially more expensive to manufacture.

The precipitation technique involves the chemical reduction of a gold solution, such as gold chloride, under controlled temperature, agitation, and addition rates. The first stage in the formation of the powder is the nucleation of gold embryos, which further grow into distinct particles, as the process proceeds. It is possible to halt the process at this stage and harvest the nanometer size embryonic precipitate. Because of the small size, however, severe agglomeration would occur if the precipitate is dried. To make a useful product for paste manufacture, the precipitate must be transferred from an aqueous medium into an organic solvent.

A 300 nanometer suspension of gold particles in an organic solvent was used to develop a thin-print etchable gold paste. The extremely small size of the gold particles required innovations in organic binder and the organic vehicle systems to keep the very dense film from blistering, provide adhesion, and produce good leveling. Additionally, it was necessary that the etched area be clean and devoid of colored residue from the binder system.

## Experimental

Substrate Preparation: The newly designed gold ink was screen printed on 2”x2” 96% alumina and polished 99.5% alumina substrates in a clean room environment. Both polished alumina and unpolished alumina substrates were evaluated in this work. Two separate print/dry/fire operations resulted in a total average thickness of ~2.5 microns (see Figure 1), and 100% coverage, with only minor void formation. A 60 -minute, 850°C furnace profile was utilized to minimize the possibility of blistering. Figure 2 illustrates the microstructure of a typical fired film. Note the very fine grain size, high fired density, and low void density.

The following process and materials were used to etch fine lines, as well as resonant rings for microwave measurements. The fired substrates were cleaned in methanol and baked at 150°C for one hour to drive out moisture. Shipley S1800 positive acting photoresist was applied at 4000 rpm. The resist was soft baked at 115°C for one hour. A 453 nm UV source was used and the parts were exposed for 25 seconds. The exposed parts were developed using Shipley 351 developer and rinsed clean with DI water. A potassium iodide/iodine solution was used to etch the parts. The coupons were then cleaned in DI water, inspected, and immersed in Shipley 1165 to remove the remaining photoresist. Figure 3 shows the narrow line width and crisp edge definition of a fine line circuit fabricated with 4550 gold ink and the etching process described above.

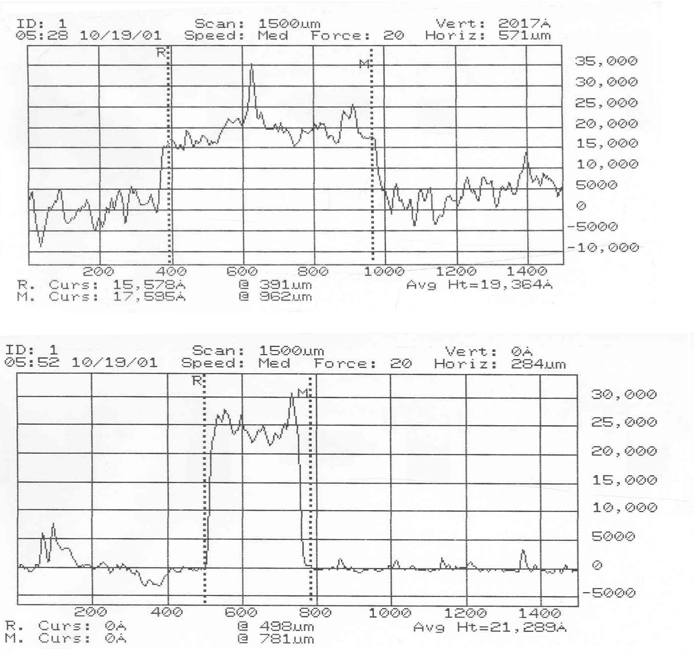

*Figure 1: Surface profiles of fired Au ink on a) unpolished as fired alumina and b) polished alumina. Vertical scales are in angstroms.*

<u>High Frequency Testing:</u> A 2.5 D EM simulation tool was used to design a ring resonator for use in characterization of the surface resistance for the gold ink. This structure, illustrated in figure 4, has been widely used and allows for the separation of dielectric and conductor losses since the dielectric loss in this case is well known. Two separate designs were used for the polished and unpolished substrates due to the fact that the respective thicknesses are different (10 mils for the polished substrate, and 25 mils for the unpolished substrate). Both designs are based on 50 Ω microstrip transmission lines. The top ring structures were fabricated from the new gold ink and the ground planes were fabricated using a standard thick film silver ink, KOARTAN 6111.

On wafer probing was used to measure the S-parameters of the completed resonators in conjunction with an HP8510 vector network analyzer. The $S_{21}$ data was then used to extract the loaded Q of the structure at each resonance. The unloaded Q can then be found from the equation,

$$Q_O = Q_L/(1 - 10^{-L/20})$$

where L is the magnitude of the $S_{21}$ peak at the resonance frequency in dB. It then follows from transmission line theory that the three contributions to the overall unloaded quality factor can be expressed as

$$\frac{1}{Q_o} = \frac{2(\alpha_r + \alpha_d + \alpha_c)}{\beta} = \frac{1}{Q_r} + \frac{1}{Q_d} + \frac{1}{Q_c}$$

where the αs are the attenuation coefficients, and Qs represents the quality factors. The three subscripts denote radiation, dielectric, and conductor loss respectively. $Q_o$ is the unloaded quality factor of the resonator. This expression is very useful since it allows the separation of the conductor and dielectric losses based on know standards.

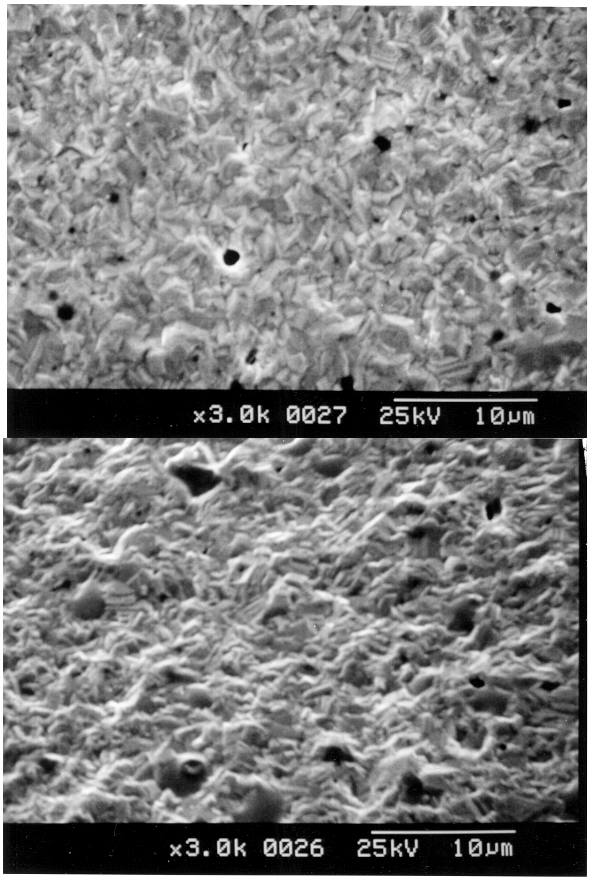

*Figure 2: SEM micrographs of fired Au surface in a top view and at a 45$^o$ angle to normal respectively. Note the presence of small voids.*

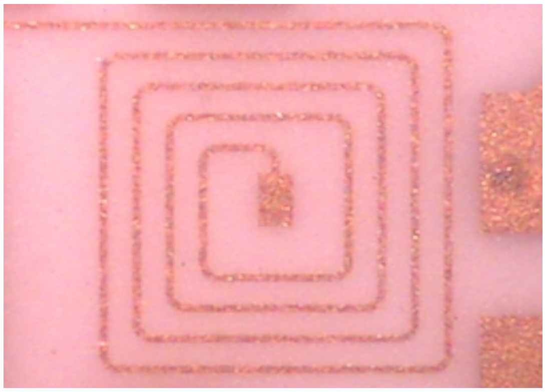

Figure 3: Micrograph of a fine line (0 .0013”) circuit showing a serpentine inductor.

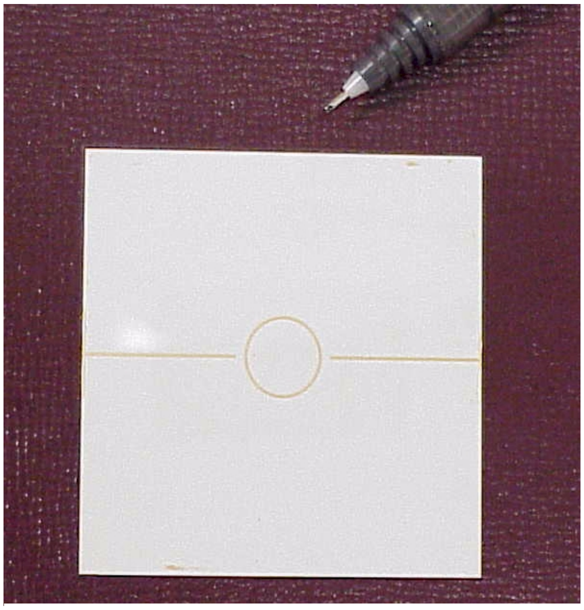

*Figure 4: Ring resonator circuit used for conductor characterization.*

The radiation loss is very small and will be neglected in this work. Since the electrical properties of the dielectric used to fabricate the samples, alumina, are well known, the dielectric loss can be calculated directly as

$$\alpha_d = \frac{k_0 \varepsilon_r (\varepsilon_e - 1) \tan\delta}{2\sqrt{\varepsilon_e}(\varepsilon_r - 1)} Np/m$$

where the dielectric constant is $\varepsilon_r$, the effective dielectric constant for the microstrip case is $\varepsilon_e$, and the loss tangent for the alumina substrates is $\tan\delta$, and $k_o$ is given by

$$k_O = \frac{2\pi f}{C}.$$

Based on these calculations the loss of the dielectric can be quantified. This then allows for the direct calculation of the conductor loss in the sample since the total losses is simply the sum of these two quantities. Therefore, the conductor loss in the ring resonator is given by

$$\alpha_c = \frac{\beta}{2Q_O} - \alpha_d.$$

From this quantity the surface resistance of the sample can also be calculated for a given frequency.

**Microwave Performance:**

Based on the above calculations, the new gold ink exhibits a surface resistance $R_s$ equal to 40 mΩ /sq. at a frequency of 4 GHz. For comparison purposes the researchers have used the same method to evaluate thin film sputtered copper on alumina, and the surface resistance of 2 microns films of copper is normally ~24 mΩ. In addition, it should be noted that this figure reflects the combined loss of the top ring structure and the loss in the ground plane. As a result, the actual loss of the Au ink is lower than the measured 40 mΩ /sq. since the silver ink was a high frit conductor that is not optimized for microwave applications.

**Conclusions**

This work has demonstrated the high frequency potential of a thin printing gold conductor. This conductor can be printed and etched on polished or unpolished ceramic substrates with fired thicknesses as low as 2.5 microns. Fired films exhibit a high degree of substrate adhesion and film density with a low rate of void formation.

Initial investigations of the microwave behavior of this new conductor system illustrate that it has the potential to approach the surface resistance of thin film gold without the need for costly thin film deposition equipment.

## Future Work

While the initial films are highly dense and the number of voids is small, additional efforts are underway to further reduce the void densities. Even a small number of voids can impact the high frequency performance and therefore should be avoided if possible.

Additional efforts are also under way to characterize this material through further high frequency measurements. A second set of samples, with the new thin gold metal forming both the resonant element and the ground plane, are currently under development. These new samples will allow for a more complete characterization of the true potential of this new material system.

## References

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