USING ELECTROCHEMISTRY IN DEVICE PROCESSING ON POLY(TETRAFLUOROETHYLENE) SUBSTRATES

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ABSTRACT

By combining electrochemical and electroless metal deposition processes with standard optical lithography and wet chemical etching, we have developed techniques for the fabrication of fine (< 20 µm), adherent, conducting features on poly(tetrafluoroethylene) (PTFE) substrates. These techniques are less expensive and have demonstrated resolution of at least a factor of five better than existing printed wiring board-based processes. Using these PTFE-based processes, we have fabricated ~10 GHz coupled-line quadrature (Lange) couplers, for which test results will be presented.

INTRODUCTION

Patterned copper on PTFE (also known by the du Pont trade name Teflon®) is used as a basis for current printed wiring board (PWB) technology in demanding, high-frequency applications. PTFE has a low dielectric constant (~2.0), low dissipation factors, high thermal stability, and high chemical resistance (1,2). For these reasons, PTFE is an excellent substrate for devices that operate at frequencies above 30 MHz or require closely spaced feature sizes that cause capacitive coupling problems. The ongoing push towards higher frequency operation and smaller feature sizes in devices makes PWB fabrication on PTFE even more attractive. While the chemical and physical inertness of PTFE are desirable, certain standard integrated-circuit (IC) processing steps are challenging due to the low surface energy of PTFE: it is extremely difficult to get metal to adhere to virgin PTFE. In current PWB manufacture, Cu patterns on PTFE are produced by first mechanically rolling an etched Cu foil with PTFE and then patterning it using photolithographically defined subtractive etching. The combination of the macroscopic Cu film with the subtractive wet etching process seriously limits fine-line resolution (1). This limitation has been discussed by Louw and Nortier (3) for the specific case of fabricating Lange couplers.

By combining electrochemical and electroless metal deposition processes with standard optical lithography and wet chemical etching, we have developed techniques for the fabrication of fine (< 20 µm), adherent, conducting features on PTFE substrates. In the example presented here, the design criterion was for features separated by less than 20 µm, but, given appropriate control of PTFE surface morphology, resolution much better than this should be attainable. The success of these processes, however, is critically dependent upon the use of a sodium napthalenide chemical etching step to treat the virgin PTFE to allow subsequent metal adhesion. The developed metal-patterning-on-PTFE processes will be presented in this paper. We will also show photographs of, and present

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limited electrical and microwave test results for, coupled-line quadrature (Lange) couplers which were fabricated using our processes on PTFE. For more information on Lange couplers, see reference (3) and the references within. The Lange coupler is designed for microwave operation at frequencies between 5 and 15 GHz. Lange couplers are used to combine or separate power, and efficient coupling at the designed operating frequency is critically dependent upon the spacing between the lines and the line width. Thus, a Lange coupler is a strenuous test for the new technologies introduced here.

EXPERIMENTAL DETAILS

All PTFE samples were cut from the same 1.3 mm-thick commercially available sheet. The samples were cleaned, then etched at room temperature for ~30 sec using a sodium napthalenide solution (Poly-Etch, Matheson Gas Products or Tetra-Etch, W.L. Gore & Assoc.) and then rinsed with solvents and blown dry. The procedure (adapted from reference (4)) for ~2000 Å thick electroless Cu deposition was a three-step solution-based process consisting of Sn sensitization, Pd nucleation, and electroless Cu deposition. To pattern photoresist on Cu, a fourth Sn immersion plating step, to aide resist adhesion, was required. The photolithography processing steps were performed in a Class-100 cleanroom. For the electroless Cu-based process, ~2.5 µm thick OCG 875-90 cs photoresist was used. For the electroplating-based process, ~6 µm thick AZP-4620 photoresist was used. Electroplating of ~4 µm thick Au was performed in a glass beaker containing a gold sulfite plating solution @50 ^oC (Englehard ECF 62). Photoresist removal was performed by liftoff in acetone. After resist removal, the seed layer on the electroplated PTFE samples was removed to allow electrical isolation between the plated metal features. This was performed by dipping the samples in a simultaneous Sn- and Cu-etchant (0.62M $FeCl_3$) for ~30 sec, rinsing in DI water for 5 min, and blowing dry with filtered N_2.

PROCESS DEVELOPMENT & RESULTS (5)

The goal of this work was the fabrication of a metal pattern on a PTFE substrate with feature sizes that have not been previously possible. With these smaller feature sizes, new design rules could be incorporated into the layout of a microwave device element with enhanced performance. Presently, in Sandia's PWB development laboratory using the commercial (mechanically rolled/ subtractive etch) process, the resolution limit for circuit production is ~75 µm. In contrast, using conventional contact-print photolithography, sub-micron feature-size resolution is routinely achieved on GaAs, Si, and other "conventional" substrates. Thus, the objective of this work was to demonstrate the combination of conventional IC fabrication techniques with our newly developed technology for producing adherent metal layers on PTFE. Consequently, a Lange coupler was designed with feature size/separation limitations of 15 µm, one-fifth the size of previous design rules. The Lange coupler was designed for application as a passive microwave element which would operate at frequencies of 5 to 15 GHz. To fabricate the device, two separate approaches were taken: an electroless plating-based process (I), and an electroless and electroplating-based process (II). Slight modification in processing parameters for some steps were required, but both approaches were built upon conventional processes.

Fabrication of the test circuit using electroless Cu was first attempted. After resist patterning, ~2000 Å of electroless Cu was deposited with the somewhat surprising result that adherent Cu was deposited onto the exposed, etched PTFE but not onto the photoresist. We believe this to be a result of failure of the Sn/Pd sensitization/nucleation steps to deposit Pd^{o} nucleation sites, which in turn could result either from failure of the Sn^{2+} to adsorb onto the photoresist, or a chemical interaction between the Sn^{2+} and the photoresist that thwarts reduction of Pd^{2+}. Regardless of the basis for the absence of Cu deposition on the photoresist, this greatly facilitated the resist removal step.

Using Process I, test circuits were fabricated with varying degrees of success, but problems associated with the use of photoresist directly on etched PTFE and consideration of the optimum design needs for microwave devices suggested that a better, more versatile process could be found.

To increase the patterned metal thickness for performance at > 5 GHz, as well as to alleviate the problems associated with direct photoresist patterning onto the etched PTFE surface, development of a more versatile process, Process II, was initiated. A schematic representation of Process II is shown in Figure 1. To deposit the thick metal layer, we substituted electroplating for electroless deposition because the electroplating process has essentially no thickness limitation (limitations are determined by the photoresist masking process), is very economical (metal is only plated where needed), and it is a relatively simple process.

Process II was used to successfully fabricate the test circuit with thicker (~4 μm) patterned metal. Optical micrographs at different magnifications of the test circuit on PTFE are shown in Figure 2. The test device consisted of 200 μm-wide by 4 mm-long microstrip conductor lines separated by 17 μm gaps. The 17 μm gap is roughly one-fifth the size previously possible using the commercial process in Sandia's PWB development laboratory. The features are uniform with sharp edges. The achievement of this relatively small patterned space allows for new design rules for devices and wiring layouts on PTFE.

The fabricated test circuit, shown in Figure 2, is a 90-degree hybrid power combiner (or Lange coupler) designed to operate between 5 and 15 GHz. Functionally, a Lange coupler operates by capacitive coupling. The input and output microstrip lines either have a direct DC connection or are capacitively coupled to each other. Leakage currents were characterized from -8 to 8 V between all adjacent microstrip lines. Measured leakage currents per unit microstrip length were less than 0.13 pA/mm; this value represents the resolution of the DC measurement equipment. The microwave performance was characterized between 45 MHz and 18 GHz. Although device design and packaging limited performance, the basic design criteria were obtained: equal power splitting was observed between through and coupled ports from 5 - 14 GHz and an approximately 90-degree phase shift was observed from 5 - 9 GHz.

SUMMARY and CONCLUSIONS

Using standard integrated-circuit processing techniques in combination with electroless and electroplated metal deposition we have developed two new processes for the adherent patterning of fine (< 20 μm) conductive features on PTFE substrates. These feature sizes are ~one-fifth the size of those that are currently obtainable using a commercial PWB process. The most versatile electroplating-based approach uses ~4 μm of plated Au onto a continuous Cu/Sn seed layer. Adhesion of the metal pattern for all of the processes depends upon successful substrate preparation by etching the PTFE in a sodium napthalenide solution.

With these processes, we have fabricated a 90-degree hybrid power combiner (a strenuous test of this technology) that has excellent DC characteristics and demonstrated promising microwave performance. DC leakage currents per unit length of adjacent microstrip conductors on etched PTFE are less than 0.13 pA/mm. Microwave performance, although limited by device packaging, yielded equal power splitting between through and coupled ports from 5 - 14 GHz with an approximately 90-degree phase shift from 5 - 9 GHz. Based on these results, we are optimistic that by using these new processes, we can incorporate other hybrid passive components, such as thin- film resistors, directly onto PTFE substrates along with our already demonstrated Lange coupler. Work is underway to demonstrate this goal.

ACKNOWLEDGMENTS

The authors would like to thank W. Worobey and R.T. Knudson for useful technical discussions on PWB processing and microwave circuit design information, respectively. This work was performed at Sandia National Laboratories and supported by the U.S. Department of Energy under contract DE-AC04-94AL85000.

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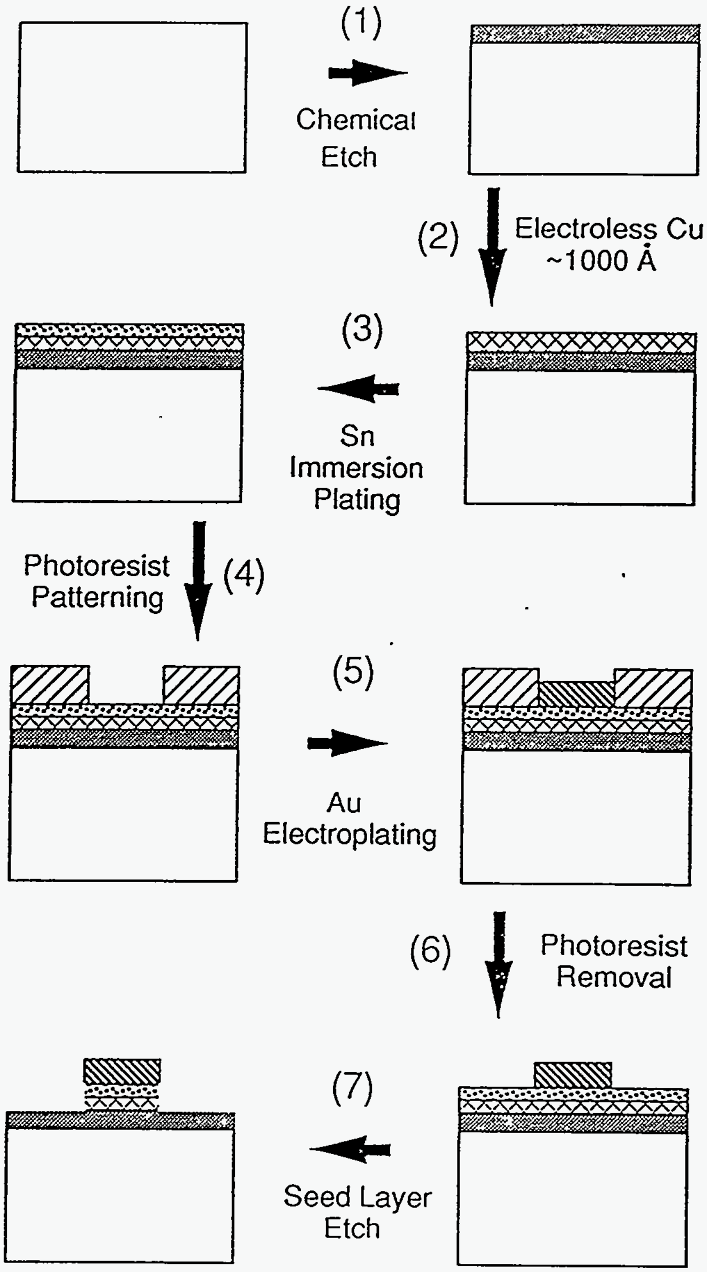

Figure 1. A schematic representation of the electroplating-based process (Process II) for circuit fabrication directly on PTFE.

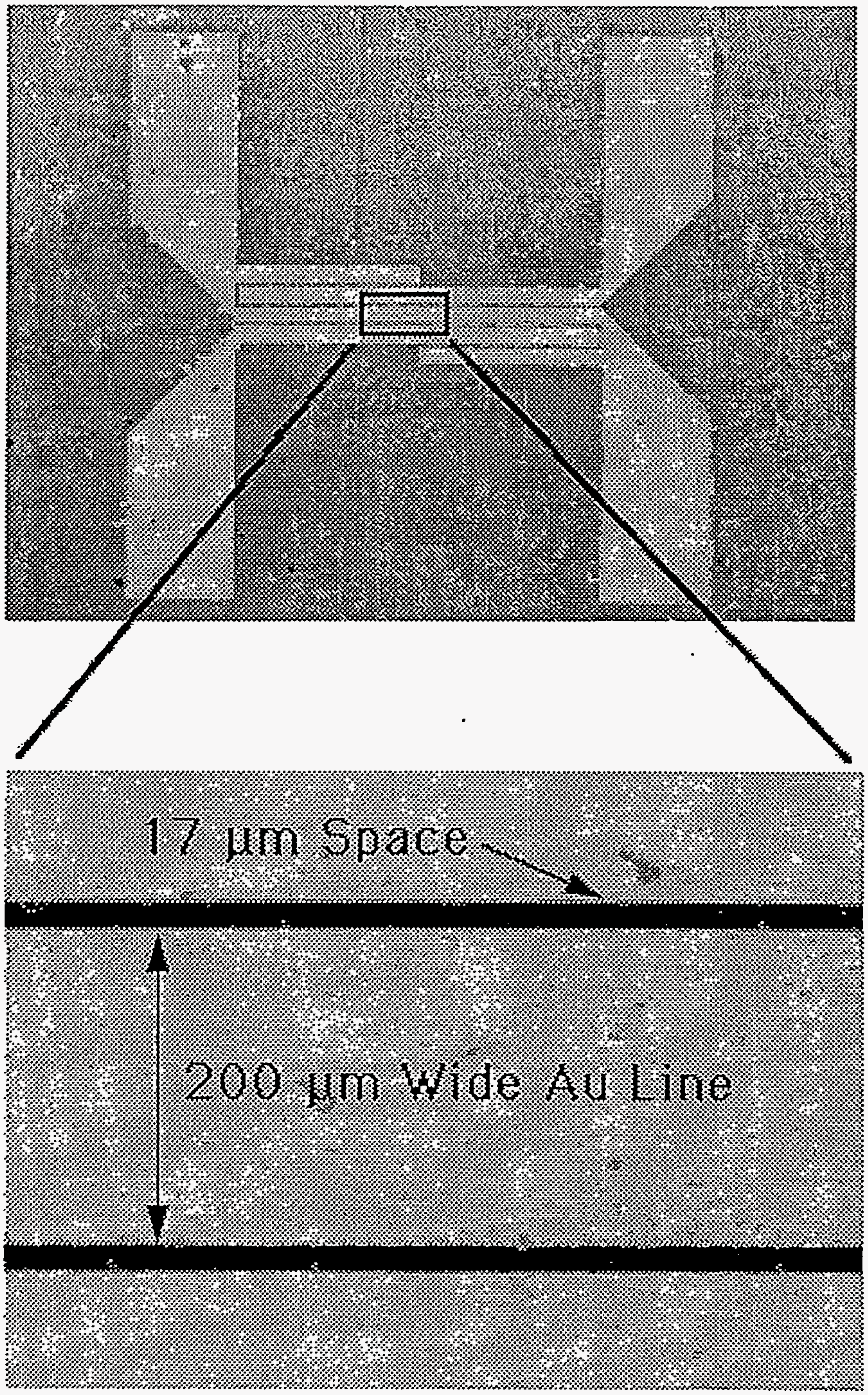

Figure 2. Optical micrographs at two different magnifications of a Lange coupler which was fabricated using Process II. Note the unifrom fine metal edge definition along the 17 µm space that exists between the adjacent 200 µm-wide microstrip lines.