MultiLythics

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Pad Printer for Electronics

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MASTER

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Contents

Section	page
I. Executive Summary	1
II. Background	2
III. Objectives	4
IV. Strategy	6
V. Clichés	7
VI. Ink	10
VII. Pad	15
VIII. Machine	18
IX. Characterization and Results	22
X. Commercialization	29
XI. Deviation from Schedule	33
XII. Financial Summary	34
XIII. Acknowledgements	34
XIV. References	35

Appendices —

*Reprints - removed
for separate processing*

Figures

Figure:	Caption:	page:
1	Typical print from polymer cliché. Traces are 50 μ nominal.	8
2	SEM photograph of laser-machined alumina cliché. Grooves are 30 μ wide and 22 μ deep.	9
3	SEM photograph of two arrays of 25 μ lines and spaces pad printed using laser-machined alumina cliché.	9
4	Electrode pattern double-exposed with half-tone screen. Height = 1.5 mm.	13
5	SEM photograph of as-received RuO ₂ powder.	14
6	Schematic of transfer cycle.	17
7	Schematic 2nd prototype printer, showing principal modules.	19
8	Print showing pituitous ink. Traces 25 μ nominal.	23
9	SEM photograph of fracture through substrate and print. Average print thickness 2.8 μ .	25
10	SEM photograph of fired electrode.	28
11	Prototype Pad Printer	31
12	Prototype Pad Printer Details	32

I. Executive summary

This is the Final report on DARPA-sponsored development Program

Pad Printer for Electronics DE-FC04-95AL87486

which was initiated in February, 1995 and intended to run 24 months to February 1997. The Program has significant value to the Thick Film processing industry, an electronic manufacturing alternative for producing functional modules integrated at the multichip level. The result is highly reliable, high volumetric efficiency, subassemblies for military applications and for commercial applications in severe environments, such as automotive, portable communications, and bio-implantable devices. The program progressed quite satisfactorily through 19 months, when it encountered severe, non-technical, difficulties. Resolving these difficulties resulted in several months of delay in completing the Program, but resulted in only a trivial increase in total program cost and no increase in cost to the sponsor. The principle Objective of the Program was the development of a printing system -- machine and appropriate inks -- compatible with existing thick-film processing but offering a 5x improvement in line density. This objective has been met. The Pad Printer is capable of printing suitable inks in traces 25 μ wide on 50 μ centers to a fired thickness of 3 μ ; each of these parameters is roughly 1/5 the value of the current alternative, silk-screen printing. The available inks represent an assortment of conductor, dielectric, and insulator formulations and the knowledge developed permits extending this family of inks to new and diverse functional materials. An important secondary objective was maximum compatibility with existing Thick Film processing; the printer and ink systems may be substituted directly for the silk screen printers in existing processes. The Program reached or exceeded its other Technical Objectives in almost every case and, in those few instances where the objective was only partially met, work continues under private funding. Commercialization of the development has been begun and is progressing vigorously.

II. Background

A. The Customer

The so-called Thick Film industry is an important segment of the world electronics industry that has been developed and remains dominated by US firms. It is an important segment of domestic electronics manufacturing -- estimated sales in 1996 exceed \$4. Billions -- and is almost equally divided between military and commercial markets. The essentials of a typical thick film manufacturing process are as follows:

- Purchase alumina substrates (100 mm sq. x 0.6 mm thick) from one of three domestic and 5 global suppliers. These are fabricated to stringent standards of strength, flatness, smoothness and dimensional accuracy and are used as support for the process and the resulting circuits.
- Purchase a large assortment of "inks" from one or more of four domestic and 5 global suppliers. These inks consist of inorganic pigments having desirable electrical function (resistors, dielectrics, conductors, etc.), glass frits to bond the

pigments to one another and to the alumina substrate, and relatively complex mixtures of organics to disperse and suspend the solids and facilitate "printing".

- Purchase screens (300 mm square inside dimensions) made by stretching woven stainless steel wire mesh (325-400 wires/in) and attaching it to cast aluminum frames. Screen tension and uniformity is very important and the screens are usually supplied with a controlled thickness of photo-polymer emulsion.
- Design patterns which will translate into wiring, resistors, passivation layers, and the like -- 12 or more layers per finished circuit in many instances. Depending on the design size of the finished circuit, these may be "stepped and repeated" to fill the 100 mm sq. workspace.
- Transfer those patterns photolithographically to the screens.
- Print or stencil the appropriate ink through the screen onto the substrate. Printing is accomplished by extruding a puddle of ink through the opened holes in the screen by an elastomeric "blade" called a squeegee which is dragged across the screen. This process is a carefully automated version of the classic "silk-screen" process used to make T-shirts.
- Dry and fire the ink. Drying removes the solvents; firing removes any remaining organics and fuses the glass/inorganic powder mixture to itself and to the alumina substrate.
- Repeat the preceding two steps as many times as necessary to assemble the finished circuit(s).
- Separate the workpiece into individual circuits as necessary. Typically each of these circuits lacks only the semiconductor die to provide some complete electrical function. The die may be added 'bare' or encapsulated; connection to the die may be by solder or wire-bonding; final assembly may be done by the thick film manufacturer or by his customer.
- Inspect, pack, and ship.

B. Strengths

The Thick Film manufacturing process has a number of attractive features. It uses the functional materials relatively efficiently, so that the volumetric efficiency of the resulting circuits is high. It has relatively low cost of entry; i.e., the capital cost of the manufacturing equipment is reasonable. It has great flexibility -- the sequence from design to testable prototype can be compressed to a day or two. The suite of available "inks" provides it with great versatility -- a wide range of parametric values of a generous array of functions can be fabricated. Finally, it has been in continuous use and continuous improvement, for military and demanding commercial applications for decades and has developed a deserved, documented, reputation for reliability under extreme conditions. As in semiconductor chips, there is a strong, "built-in", incentive to miniaturize, because manufacturing costs are accumulated on a per-substrate basis and the smaller the individual circuits can be made, the more circuits can be yielded from a given substrate.

Although in the "typical" process, a rigid (pre-fired) alumina substrate was the indicated "target" for printing, the process has been extended to ceramic "greenware", to printed circuit boards, and to a variety of other "ware". The manufacturing process applies to multi-layer co-fired devices such as capacitors and ceramic packages for semiconductors.

C. Limitations

On the other hand, the process has certain limitations. It has only modest productivity, in part because of the modest substrate size and in part because holding screen precision over larger workspaces is difficult. This productivity limitation has tended to restrict its use in high volume markets. More important by far, while the resolution and precision of other circuit manufacturing processes has been increasing constantly, the thick film process has been unable to improve resolution beyond roughly .005" (125 μ) lines and spaces. Competing technologies have significantly reduced the large advantage in volumetric efficiency that it once had. Another factor that is both a strength and a weakness is the large input, of both materials and technology, from suppliers. This is a strength in broadening the capabilities of the manufacturer; but, because it dilutes critical development efforts, it limits technological advance in the field.

D. Requirements

The objective of this Program, then, has been to correct the critical deficiencies that limit the performance of thick film technology while preserving, to the greatest extent possible, the advantages that distinguish it. In greater detail:

- improve by at least a factor of 5 the intrinsic resolution of the printing process
- eliminate or reduce size constraints
- preserve the materials suite
- preserve (modified only for scale) design rules
- preserve the ease of prototyping and short production runs
- preserve economy of capital equipment (indeed, preserve as much of the existing process equipment as possible).

E. The Team

To that end, a consortium was formed. Three companies, each small businesses, and each bringing particular expertise, combined to "re-invent" the printing step in thick film processing. First, MRA Laboratories, with long experience in the fabrication of electronic "inks", was enlisted to reformulate conventional thick film inks with finer particle size pigments and different organics for the particular requirements of a new printer. Second, L&L, Inc. with equally long experience in custom manufacture of process equipment for the electronics industry, was asked to design and build a high-precision version of the printer to use those inks. Finally, MultiLythics, Inc. served as program management, assured that the interface between the new printer and the application remained user-friendly, and provided liaison with the sponsors. In the very late stages of

the development effort, the role of L&L Inc. has been transferred to Abacus Automation, Inc. of Bennington, VT, who are now actively involved in the effort.

The development of improved printing technology for the thick film industry is a paramount example of "dual-use" technology. The industry itself is dual-use in that its markets are almost equally divided (in dollar volume) between military and commercial applications. Furthermore, printing is a unit operation in the process, so an improvement in printing is of indiscriminate benefit to all final product users. With the generous financial and technical support of DARPA, we have completed a development that improves the infrastructure of the industry and therefore contributes significantly to both markets. .

III. Objectives

A. Pixels

The resolution problem of conventional thick film screen printing is intrinsic. The ink is extruded by a squeegee through square holes defined by the screen wires. The wires of the screen are of finite diameter and spacing, resulting in "pixels" which are 64μ (for 400 mesh) to 78μ (for 325 mesh) apart on centerlines. Each hole or pixel is either filled with polymer emulsion or not -- even though the emulsion can be removed from 'fractional' holes, the hydraulic pressure provided by the squeegee is largely ineffective for partially cleared holes. The rheology of the thick film inks is intended to be shear-thinning -- relatively low effective viscosity at the high velocities attained passing through the screen, but relatively high effective viscosity at low shear rates so that the edges of a print are well defined. Practically speaking, the result of these compromises is minimum line width of about three "pixels". The limitation on line spacing is even more severe because the polymer which is intended to exclude ink has very little area of attachment to the screen and may be lost mechanically. The first goal of the development, then, was to eliminate pixels -- to implement a printing method which had an intrinsic precision significantly higher than the target dimensions for lines and spaces.

B. Guidelines

Preferred or target dimensions for line width and spacing may be deduced from a very simple calculation. When the DC resistance on a signal line equals the characteristic impedance of that line, reflected signals are minimized; when the DC resistance exceeds the characteristic impedance, signal attenuation becomes a concern. For a large majority of high frequency circuits, a characteristic impedance of 50Ω is preferred. Therefore the DC resistance on the longest trace should not exceed that value. The intrinsic resistivity of metals and alloys is predetermined so, for any conductor, the necessary cross-sectional area to yield a given resistance/unit length may be calculated. That cross-sectional area may be obtained by narrow, thick, traces or wider, thinner, traces but for several reasons wider thinner traces are favored. Thick traces are harder to print over; indeed the accumulation of surface roughness is a significant yield problem in all additive circuit technology. As characteristic circuit frequencies continue to increase, the skin-effect phenomenon becomes more important -- the interior of the conductor carries less current so a large perimeter results in lower effective resistance. Under ideal circumstances of fully dense, planar, homogeneous traces in pure copper or pure silver, a trace 100 mm long

(typical of the longest trace using "Manhattan" wiring on a 50 mm square substrate) would need to be 13μ wide by 2.5μ thick to meet the resistance requirements. In the "real world" traces are less than fully dense because of the need for glass frit to promote adhesion, are alloyed to reduce dissolution into solders and to minimize electromigration under bias voltage, operate at temperatures above room temperature, and are rough due to the underlying substrate. Recognizing these limitations, we selected as target print parameters 25μ wide lines and spaces and the same 2.5μ thickness.

To maintain 6σ confidence in continuity in a 25μ wide line, one should be able to control line width to $\pm 4\mu$. In turn, $\pm 4\mu$ control of other feature sizes, particularly of resistor prints, permits resistors to be printed to tolerance limited primarily by thickness control; if thickness control is at least as good as $\pm 0.1\mu$, it is reasonable to expect $\pm 5\%$ resistors as printed and fired. Minimizing or eliminating trimming of resistors is desirable and, in digital circuits at least, extreme precision of resistors is often not necessary.

C. Precision

Truly exploiting 25μ lines and spaces requires three more-or-less independent kinds of precision:

- precision of individual features,
- precision of feature location throughout a single print, and
- precision of feature location between successive prints.

Precision of individual features depends on pattern-making and the rheological behavior of the inks used. Together these factors control the volume of wet ink per unit length of trace and hence the sheet resistivity of that trace.

Precision within a print depends on the quality of the pattern -- e.g., a low thermal expansion coefficient or a well thermostatted printing environment so that cumulative uncertainties in feature location are small. It also depends on freedom from distortion due to the printing process -- it is well known that silk screen printing produces a "bow-wave" of image distortion due to stretching of the screen under the frictional force of the squeegee. Although acceptable in low-resolution printing, this distortion would not be acceptable when the goal is 25μ lines and spaces. Because errors due to thermal expansion mismatches are cumulative, they represent limitations on the maximum practical "workspace" or area printed in a single action. Attention to such errors permits increasing the workspace and therefore the productivity of the printing process. To preserve the present 100 mm (substrate) workspace, cumulative errors may not exceed $\pm 9\mu$ in 100 mm or roughly half a line width for the two most widely separated points on a 100 mm sq. substrate ($\pm 12.5\mu$ in 141 mm). As will be seen below, this goal has been met.

Maintaining precision between successive prints depends critically on the design of the printing machine. It must be possible to position the pattern relative to the substrate with great confidence repeatedly, since the substrate must be removed, dried and frequently fired between successive prints. To make practical use of 25μ lines and spaces the uncertainty in relative position of successive prints must not exceed $\pm 10\mu$. This is an unfortunate value. Even though the substrate is hard, wear-resistant, and dimensionally

stable, loading it manually against mechanical reference points or "stops" cannot consistently achieve better than $\pm 25\mu$ position accuracy. Optical location is capable of the higher precision desired, but is significantly more expensive. As will be seen below, this represents one of the significant cost "breaks" in the final machine.

D. Incidental Benefits

Again, the goal was to preserve the principal advantages of the thick film process - ease of prototyping, economy of short runs, and as many of the auxiliary components of the manufacturing process as possible. This implies minimum perturbation to the materials suite, minimum perturbation to drying and firing cycles, familiar design rules (even if rescaled) and the like. Particularly important, for ease of introduction into the manufacturing environment, the balance of the fixed investment of the manufacturer should remain useful and only the silk screen printer itself should become obsolete. Test equipment, design tools, indeed all the peripheral equipment, either remain useful as-is or at most have to be modified by adding finer-resolution probes.

IV. Strategy

A. Transfer Printing

A number of printing alternatives were examined. At least somewhat surprisingly, many were easily capable of the in-plane resolution that was desired. Almost all commercial printing -- newspapers, magazines, maps, etc. -- are printed using so-called "offset" lithography. An image is etched photolithographically into a master plate or cliché, ink is applied to it, and the ink is transferred to the workpiece (paper) by "offsetting" it to an elastomeric transfer pad. Even when "pixels" are used, they are chosen for convenience, not due to some intrinsic limitation of the process. These transfer processes are

- high speed -- orders of magnitude faster than silk screen printing
- moderately high precision -- $\pm 40\mu$ registry of successive images is better than current screen printing, though not good enough for 25μ lines and spaces
- high resolution -- easily 25μ spacing between features, with significant "gray scale" size control over the features themselves
- capable of "pixel-free" imaging.

With a single exception, these transfer processes share a common limitation: they are optimized for speed and resolution by minimizing print thickness. Typical print thicknesses, dry, are well under 1μ yielding prints that, even with appropriate pigments, can not be expected to yield useful electrical properties.

B. Pad Printer

The singular exception to this general observation is the so-called Pad Printer. Pad printing still uses a transfer medium -- an elastomeric "pad" -- to transfer ink from a pattern (a cliché, in the industry) to the ware. In this instance, however, the ware is often china (dinnerware) and the ink consists of low-visual-contrast pigments which must be

comparatively thick to provide visual appeal. Therefore the pad must transfer relatively large volumes of ink to a rigid, often non-planar, target. This is accomplished by engraving relatively deep grooves into the cliché, filling those grooves by flooding with ink and scraping ("skiving") the excess away with a hardened blade, then transferring the ink on a highly compliant pad. This seemed a particularly attractive starting point for a high-resolution thick-film printer, the objective of this program.

The manufacturers of existing pad printing equipment have made no effort to achieve the precision required by the intended electronic application. Inks for these printers have not been designed for electrical function. Finally, the very large elastic compliance in commercial pad printers, an advantage in printing on dinnerware, makes it essentially impossible to locate prints with sufficient accuracy for electrical function. These existing limitations of the process served to define the necessary incremental "inventions". The program goal was to re-engineer the pad printer to obtain the necessary precision and to modify the existing thick film inks to enable them to be printed using the pad printer. Note that this necessity to simultaneously engineer the machine, the transfer pad and the inks used by the machine explains why this development has not been undertaken earlier. The industry historically has bought inks from vendors and bought printers from different vendors. The user has not had the capability to engineer a system and the vendors have not had any incentive to replace existing and profitable businesses with an alternate system. Ink makers, in particular, would not be excited to learn that the same number of functional circuits can be made with 20% of the purchased raw materials. Equally, in the absence of ink, producing a high-precision machine is fruitless. Note, in particular, the unsuccessful efforts in Finland¹ to make usable inks by diluting existing thick-film formulations.

V. Clichés

A. Requirements / prior art

The essential pattern plate for the pad printing process is called the cliché. It is normally a flat plate (of aluminum or steel) into which a positive image is etched or engraved to controlled depth. Control of the image in its own plane (X, Y) dictates the precision of the transferred image and the control of the image groove depth (Z) dictates the volume of ink transferred and hence the thickness of the dried and fired image. In planning the development of the Pad Printer, little time was budgeted to cultivating a source of clichés. Innocently, it was concluded that, since trace resolution in the semiconductor industry was below 0.5 μ and even in the printed circuit board industry 50 μ lines and spaces were becoming available, etching 25 μ features would be straightforward. This was a mistake. The critical neglected factor was the aspect ratio required in the cliché. Not only were 25 μ lines on 50 μ centers required, but the lines are required to be at least 25 μ deep. Since conventional etching is essentially isotropic in attack, the groove required would have to be initiated on a photopositive line of zero width.

B. Proven Options

After an extraordinary amount of effort, two workable solutions have been found to the problem of clichés -- neither entirely satisfactory -- and efforts to find a better cliché

continue. The two forms of cliché which are usable are at extremes of cost and performance. At the "economy" extreme, if printed circuit board stock (FRP) is coated with a controlled thickness of photopolymer, exposed and developed, and used "as-is", the result is a quite satisfactory cliché for a very modest number of prints. See a typical print made from a photopolymer cliché in Figure 1. This is fast, cheap, convenient, and reasonably precise -- quite satisfactory for prototypes and check-prints; it is not adequate for production runs. The polymer is simply too soft to withstand the pressure and friction of the skive for very many prints. Worse, the wear of the polymer is insidious. As it thins it continues to produce cosmetically satisfactory prints, but they gradually become too thin to provide satisfactory electrical performance -- manufacturing scrap is never satisfactory.

Figure 1. Typical print from polymer cliché. Traces are 50 μ nominal

At the "performance" extreme, an excimer laser vendor was located² who is willing to do custom machining of alumina clichés. So long as high quality alumina substrates were selected for machining, the resulting clichés were superb. SEM photographs of a representative laser-machined alumina cliché are shown in Figure 2 and Figure 3 is an SEM image (from an unfortunate angle) of a representative print.

Figure 2. SEM photograph of laser-machined alumina cliché.
Grooves are 30μ wide and 22μ deep

Figure 3. SEM photograph of two arrays of 25μ lines and spaces pad printed using laser-machined alumina cliché.

These clichés displayed excellent precision in all three dimensions, low thermal expansion coefficient (of course), no measurable wear after many print cycles, and ease of set-up and clean-up. Not surprisingly, they are painfully expensive, although they might be quite satisfactory for extended production runs.

C. Candidates

No modestly priced, modestly long-lived cliché with the requisite precision has, as yet, been identified. However, four additional candidates have been investigated in some depth:

- Aluminum plates may be 'engraved' with a very small **end-mill** turning at very high speed³. The engraving is controlled by a NC table so is as precise as a CAD-file. Depth control is reported to be excellent, although the groove profile is not rectangular, so the groove will have to be of somewhat greater nominal depth to contain the same volume of ink. The cliché is hard-anodized after engraving to give it excellent wear resistance and the prices are attractive. The lower limit of this technology has just been reported to be 100 μ (.004") grooves.
- In a derivative of photo-resist clichés, one may coat an alumina plate with **Phodel**⁴, the duPont ink designed to be patterned photolithographically. It may be exposed and developed conventionally, and since it is a glass it has a naturally wear-resistant surface. Unfortunately, duPont declined to cooperate in evaluating this opportunity. Other vendors may also exist for similar materials and the search continues.
- At least one vendor offers to "**plate-up**" a cliché. He would coat and expose with a negative photoresist (leaving bare the areas in which ink is not wanted) then electroplate with nickel prior to removing the resist. The resist defines the plated deposit, giving excellent groove shape. Thickness is controlled by plating time but may be adjusted by lapping, if necessary. Electroless nickel is hard and wear resistant.
- Finally, **laser machining** of ceramic clichés should become much faster and therefore much cheaper with the use of YAG sources and frequency doublers to reach the same regions of wavelength as the excimer lasers. These machines are becoming available⁵ but none is yet accessible for experimental use.

D. Status

The majority of the results reported here are from the photo-emulsion clichés. A sufficient number of prints have been made using the excimer-laser machined alumina cliché to verify its superior performance. Marginal results have been obtained from etched steel plates and there is some indication that more care in the photolithography and etching process might make this kind of cliché usable. Etched copper was completely unsatisfactory for 25 μ lines and spaces and was marginal even at double that scale.

VI. Ink

A. Assumptions

Two assumptions guided the development of pad printing inks:

1. The same "suite" of **inorganic** materials as that developed for conventional thick film processing should be usable with only minor modification.
2. A quite different **organic** vehicle system would be required for these pigments.

Retaining familiar inorganic materials was motivated by two major goals. The first goal was to minimize the necessity for invention but the second and more important goal was to preserve the validity of the vast body of data on the reliability of these materials under environmental stress. After firing, since only the inorganic components survive, the

various electrical components should be essentially indistinguishable from their more conventional counterparts. Certain differences are a matter of intent and design. For the sake of printing resolution it would be desirable to reduce the particle size of these inorganic materials. Similarly, thinner fired prints were anticipated in the design. These changes would alter the parametric values ($\Omega/\square$ for resistors, for example), but the differences are well understood and independent of reliability issues.

The vehicle system is considerably more complex. In any ink formulation, the vehicle system is an aggregate of multiple ingredients:

- **Solvent(s).** Dissolves the remaining (organic) additives, aids in suspending the particulates, is varied to vary the rheology of the ink and the rate of drying.
- **Surfactant.** Coats the surface of the particles, aids in dispersing them from one another, "compatibilizes" them with the solvent.
- **Binder.** Provides cohesion in the dried print -- particle to particle and particles to substrate. Sometimes modified with **plasticizer** to reduce brittleness.
- **Others.** In silk screen printing, shear thinning or pseudo-plastic behavior is desirable. In pad printing, "tackifiers" are used to modify ink adhesion to cliché, pad, and ware.

As the last bullet in particular suggests, there was little reason to expect the vehicle system for pad printing to resemble very closely that for silk screen printing. There was, however, good reason to believe that a suitable vehicle system for any single pigment would be easily modified for all other pigments. Key to this is the surfactant. While it may vary depending on the pigment particle to be coated, it always presents the same appearance to the remainder of the vehicle system. Therefore, various surfactants might be necessary for various pigment types, but the remainder of the ink organic system might remain chemically constant.

B. Strategy

The strategy in ink development reflected these assumptions closely. Development began with the simplest possible "ink", the only inorganic pigment was an alloy powder of Ag/Pd which is widely used in the multi-layer co-fired ceramic capacitor industry. This powder was readily available in the desired sub-micron particle size range -- median size 0.6μ , no particle larger than 3μ -- and, because it is intended for co-firing, there is no need for glass frit to promote adhesion. The intent was to use this simplest possible system to establish a generic definition of "good ink" and then to adapt that description to other pigments. The definition itself was complex. It quickly became apparent that conventional detailed measurements of ink rheology were far less useful in the development of pad printer inks; presumably, this is because the range of shear velocities encountered during pad printing is far smaller than that during screen printing. The difficulties encountered with the manufacture of satisfactory clichés, described above, indicated that the highest possible solids loading -- corresponding to the lowest possible shrinkage during drying -- would permit acceptable dried and fired trace thicknesses from shallower engravings and hence from clichés that were easier to make, to use, and to clean.

C. *Drying and Skiving*

Another phenomenon was not immediately recognized but is obvious in hindsight: twenty-five micron wide lines having a wet thickness of 25μ or so have an extremely high surface to volume ratio and therefore dry very rapidly. Although an early machine concept involved warming the pad or the ware to control drying, instead it was necessary to replace the solvents common to silk screen inks with solvents of significantly lower volatility. This led to two concerns regarding prints in which narrow traces coexist with large electrodes:

1. Large electrodes dry significantly more slowly than do traces. This might lead to poor print definition or require greatly extended drying within the print cycle.
2. Skiving of excess ink from the cliché might be a problem for large electrode patterns. Since the depth of engraving in the cliché is of the order 25μ and the engraving for an electrode may exceed 1000μ in width, very small elastic distortions in the skiving blade might be sufficient to "scoop" a significant fraction of the ink from the electrode pattern in the cliché.

To give proper attention to these concerns, all test patterns incorporated traces ranging from the target minimum of 25μ up to at least 2.5 mm. In most instances, a wide range of feature sizes was examined by photo-imaging a primitive pattern such as that shown in Figure 1 at 1x, 2x, and 5x magnification to make the clichés. This allowed the measurement of nominally constant trace resistance at all scales, since the number of squares remained constant. An increase in measured resistance with feature "scale" would quickly reveal thinning in wider traces and features.

The first of these concerns was groundless. Large area prints seem better able to support the pad and less likely to spread under printing pressure. Also, since the edges of the print dry quite rapidly, they offer a sort of "cofferdam" for the remaining ink that allows it to dry without spreading. The second concern is valid. A number of "technique" or "setup" factors influence it strongly. Changes in blade thickness, the angle of incidence of the blade to the cliché, and blade pressure on the cliché are obvious contributors. In a local application of Murphy's law, all changes which act to minimize the "scooping" of ink from large features also make printing more highly susceptible to small defects in the skiving blade and to local roughness of the surface of the cliché. An alternative solution to this problem was briefly explored and shows promise. Since large electrode areas need reproducibility of sheet resistivity but can be redesigned for variations in its value, a photopolymer cliché was exposed first through a commercial "half-tone" screen to produce an array of dots, then exposed through the photopositive for the electrode. The result was a "half-tone" electrode with a very uniform 75% coverage of continuous ink surrounding the dots, see Figure 4. The dots provided support to the skive during printing, so the average thickness was quite uniform throughout the print.

Figure 4. Electrode pattern double-exposed with half-tone screen. Height = 1.5 mm.

As printing technique, clichés, and ink-making all improved, it became desirable to examine longer traces; primarily this was to increase the probability of finding an open in a trace (sample longer lengths), but it also gave better statistical accuracy (slightly more pessimistic results) than obtained with short traces. Since the resistance of a trace is dominated by the resistance of the "thin" or "narrow" spots, the distribution of observed trace resistance is not Gaussian, but rather Poisson; therefore we report modal resistance, not average resistance.

D. Status

Generally speaking, the development strategy outlined above was a success. When a marginally satisfactory ink was obtained using the simple Pd/Ag pigment, the same vehicle system proved to work with a variety of other pigments:

- Same alloy powder plus 5% and 10% by weight glass frit. Surface metallization.
- Higher silver alloys with frit. Economy, conductivity and surface metallization.
- Resistor formulations. RuO_2 + frit.

No special effort was made to optimize the levels of frit for the various conductors. On the one hand, it is obvious that the minimum level of frit in a conductor which gives acceptable adhesion is to be preferred. This level improves sheet resistivity and makes both wire-bonding and solder attach easier. On the other hand, investigating a higher range of frit additions was a deliberate attempt to define the limitations of trace thickness, since the presence of frit "thins" the remaining conductor. At least over the range studied, frit additions increased sheet resistivity only modestly. This suggests that, at least for conductors, considerable discretion is available to the ink manufacturer. In the case of resistor formulations -- in which the frit has the dual roles of providing adhesion and modifying the temperature-dependence of the fired resistor, that fired prints can indeed be too thin.

In each instance, the "first article" of the alternate formulation printed about as well as the "simple" ink which was the basis of the initial development. In fact, resistor formulations were consistently somewhat better than the reference conductor. At the time these trials were run, the "simple" ink was still evolving. Nevertheless, it provided great confidence that the development strategy was sound. "New" inks -- Au with frit for surface metallization and wire bonding, unfritted W for co-firing with alumina, and the like -- can be developed in a very small number of iterations from the base of knowledge that has been generated.

The initial values of TCR (Temperature Coefficient of Resistivity) of the various resistor formulations was not satisfactory. This was not a surprise. Fired resistor TCR is the result of both physical and chemical interaction between the oxide and the glass frit during firing. The physical component is the connectivity of the oxide particles; the chemical component results from interdiffusion of frit and oxide and secondary reactions between the frit and the substrate. Commercial RuO_2 is supplied as an agglomerated 4-5 μ powder consisting of sub-micron particulates, see Figure 5.

Figure 5. SEM photograph of as-received RuO_2 powder.

To convert this to a pad-printable ink, it was necessary to deagglomerate it by modest milling. Similarly, the glass frits had to be reduced in particle size to make pad printing inks. Since the surface to volume ratio of both the frit and the oxide particles were changed (increased) in order to get fine-line printing capability, the rate and extent of their interactions also changed. This is not a serious concern.

A significant user of thick film processing has entered into a joint development agreement to adapt his existing resistor inks to pad printing. This is an unusually good opportunity, because his existing inks contain significantly finer pigment particle than the industry norm and they have already been optimized for TCR. The initial effort will consist of extracting the pigment mixture from the thick film vehicle system and reformulating it in

the vehicle system developed for this program. If this pigment system behaves like the predecessors which have been examined, a very few trials will suffice to produce an excellent ink -- with good TCR. Additional detail is available below under Commercialization.

In passing, note that truly fine-line printing with resistor inks is unlikely to be necessary or popular. Because resistors dissipate power, they cannot be made arbitrarily small and, if they are intended to yield reasonably tight tolerances, they should be relatively large. There are two reasons for this:

1. To aid in targeting -- a given printing error represents a smaller percentage of a large feature dimension and
2. To facilitate trimming -- recall that the kerf and heat-affected zone of a typical laser trim is at least 40μ wide.

"Relatively large" should be defined more accurately. In existing circuits, 125μ lines and spaces are used to connect 1 mm square or larger resistors. If one assumes the same 5x increase in component density for the resistors as for the conductor traces, preferred resistors will be 200μ or larger in minimum dimensions. A significant exception to this general observation are "meander" resistors designed to reach target values by combining relatively low sheet resistivity with a large number of "squares".

VII. Pad

A. Limitations

Recall that the pad of a conventional pad printer is "large" in all three dimensions and deliberately highly compliant -- soft. A typical one might be an ellipsoid of revolution, 5-6" in base diameter and 4" or more high, bonded to a flat wooden or metal support to permit attaching it to the machine. The preferred elasticity of such a pad is quite high -- not quite Jello-like, but much like a "nerf"-ball. Although this compliance is useful when printing on irregular surfaces like china (vendors like to print on golf balls and peanuts, too), it is essentially impossible to locate successive prints to $\pm 10 \mu$ with this kind of transfer medium.

Printing for the electronics industry imposes a different set of constraints. The initial roughness of an electronic substrate is quite low (of the order $0.3-0.5 \mu$ rms) but roughness accumulates during manufacture because it is sometimes necessary to print new images over or between existing printed and fired features. The experience of the silk-screen thick film industry is that severe printing problems are encountered when 10 or more printed layers have been deposited and fired. For most designs, since not all images overlap one another, this probably corresponds to an added surface roughness of 200μ or less. Since pad printing is designed to produce fired prints that are roughly $1/5$ the thickness of conventional screen prints, pad printing might be expected, for a similar design to increase the surface roughness no more than 40μ . Therefore, the Z-axis (thickness) compliance of the transfer pad can be significantly reduced with little risk. In turn, limiting the compliance of the pad permits significantly greater control over the X and Y position of printed features.

B. Redesign

For the Pad Printer, pad compliance is reduced by bonding relatively thin (1 cm and less) layers of familiar silicone elastomer to a thin (0.38 mm) spring-steel sheet. In its own plane the spring steel is quite rigid, yet it remains quite flexible out-of-plane. The elastomer bonded to it therefore acquires dimensional stability within the plane while remaining free to deform (on a macro scale) in the Z-direction. The thickness of the silicone is adjusted to provide elastic compliance (at the micro scale) over the accumulating surface roughness of multiple prints.

C. Osculation

Out-of-plane flexibility of the pad is necessary. The experience gained in conventional pad printing makes it clear that contact between the pad and its workpiece -- either the cliché or the ware -- must progress from a single point or line "out" across the workspace. This so-called osculating (kissing) contact assures that no air is trapped in the printing plane to produce discontinuities in the prints. Equally important, the pad should withdraw from contact with the target in the same linear fashion to avoid area-dependent stresses on the pad/ink interface. As it is implemented in most pad printing, this has unfortunate consequences. The initial point of contact is (a point or line) in the center of the workpiece; this point is enlarged to an area of contact by increasing the force on the pad. Deformation of the pad under this force does indeed increase the contact area but also results in a gradient of pressure -- the initial point of contact always sees the highest pressure and the perimeter of the contact area sees little or no pressure. Initial experiments with a commercial printer confirmed that the line width resulting from an engraved groove of constant width increases monotonically with pad pressure. When the pad is pressed against the cliché, the ink is "encapsulated" by the grooves in the cliché, and the gradient in pressure is relatively unimportant. When the pad is pressed against the substrate, the ink is confined between one flat surface and one compliant surface. In this case pressure apparently extrudes ink along the pad/ware interface and a gradient in pressure results in a gradient in line widths. Consistent deformation of this sort could perhaps be accommodated in the design of the cliché but, for the common hemi-ellipsoidal pad, the distortions are a function of radial position from the axis of the pad and modifying the cliché would entail detailed knowledge about the shape and elastic parameters of the pad. It is far preferable that the maximum pressure exerted by the pad on any incremental area of the target (cliché or ware) be constant and controlled.

Conventional transfer printing (offset lithography, for example) solves this problem by transferring ink from the cliché to a cylindrical transfer roll and thence to the substrate. The roll is loaded with a small interference fit against either workpiece to force some small deformation of the elastic layer. At any instant in time, the pressure between transfer roll and either workpiece is a maximum on the line perpendicular to the workpiece and through the center of the roll and drops smoothly to zero at the "osculating" point. As the roll turns this "footprint" travels smoothly across the workpiece such that both the leading and trailing edges are smoothly engaged and released and the maximum pressure is uniform (though reached at different times) everywhere. The geometry of the transfer roll was attractive for Pad Printing as well, but it appeared to be difficult and expensive to

synchronize a transfer roll in succession to the cliché and substrate well enough to guarantee the required $\pm 10 \mu$ registry of successive prints.

D. Registry

The solution selected may be visualized with the aid of Figure 6.

- Attach one end of the pad (the spring-steel strip and the elastomer which is bonded to it) rigidly to the frame of the printer.
- Attach the other end of the pad to the printer frame through springs which keep it in gentle tension.
- Choose the mounting heights so that the pad will partially wrap around an actuator roll when it is in the "down" position.

Drive the actuator roll through a rectangular path -- "down" to engage the pad, "forward" to print, then "up" to release the pad, and finally "back" to return to the starting position. A single cycle of the actuator is shown schematically in Figure 6.

Figure 6. Schematic of transfer cycle. Sequence proceeds clockwise from top-left and repeats two times to make one print. The first cycle extracts ink from the cliché and the second (after a shift of the carrier) deposits the ink onto the "ware".

- When the actuator descends it forces the pad into contact with the workpiece (cliché or substrate) short of the image proper. Then, as the actuator moves "forward" the pad is forced to "roll" progressively across the image plane and the local deformations

and geometry are identical to those encountered in roll transfer printing. At the end of a print stroke, when the actuator lifts, the spring-steel and pad follow it away from the work vertically, but remain fixed in the plane of the cliché and ware.

When each stroke of the actuator begins the pad is in exactly the same place even if the actuator has rotated, slipped, or otherwise failed to reproduce perfectly its motions. For this to be strictly true, the surface of the cliché and the ware must be co-planar, a constraint accommodated in the design of the machine.

This pad/actuator strategy has another minor but pleasing consequence. For conventional pad printing, increasing the printed area per stroke means increasing the printing force -- to increase the deformation of the pad -- and in fact the increase in force is proportional to the increase in area, not just diameter. Also, the print area contacted by the pad is usually circular -- fine for dinnerware, less valuable for electronics. Therefore, changing the print area in conventional printing geometry requires significant changes in force. The combination of rectangular pad and cylindrical actuator proposed for the Pad Printer yields a printing mechanism which "scales" linearly rather than quadratically. A wider pad increases the necessary force linearly, while a longer stroke increases the force not at all. Therefore, the Pad Printer which at present operates in a 100 mm square workspace can be rescaled for larger workspaces limited only by errors such as result from differential thermal expansion between cliché and ware.

VIII. Machine

The attributes of the Pad Printer may be summarized in two categories: needs, and wants. Without the needs, the printer would be incapable of producing satisfactory product at an acceptable price. Without the wants, the machine would be more or less inconvenient to use, difficult to maintain or set up, less "user friendly", or less productive. Understanding these priorities, a basic machine has been developed which meets the needs at minimum capital cost. That basic machine can then be enhanced with a series of options which respond to the performance "wants" in various ways at various incremental costs.

A. Basics

The basic machine consists of five modules. Their function is briefly described below and may be better understood with the help of the schematic, Figure 7.

Figure 7; Schematic, 2nd prototype printer, showing principal modules. Position shown allows simultaneous addition of ink to cliché at INK/SKIVE and deposition of ink on ware at PRINT. TRANSPORT shifts CARRIER to left to allow simultaneous transfer of ink to pad from cliché at PRINT and removal and replacement of target substrate at LOAD.

1. **CARRIER.** Basically a plate containing two vacuum chucks to which the cliché and the ware can be temporarily attached during printing. With the exception of the LOAD reference points, the carrier is non-precision in X, and Y and preserves Z precision only by assuring that the backside of cliché and ware are co-planar.
2. **LOAD.** 3-point stops at the perimeter of the vacuum chucks on the carrier permit manual loading to a reproducibility of $\pm 20\mu$ or better. This module must fix the relative position of cliché and ware; it controls the stacking precision of the printer.
3. **TRANSPORT.** Very high precision and reproducibility in the X-direction. This permits precise positioning of the cliché and the ware under the print head and permits translation of the cliché from the LOAD position to the INK/SKIVE position and the PRINT position under program control. As the ware is attached to the same carrier as the cliché, these same motions translate the ware from a dummy position (when the

cliché is being loaded) to the PRINT position (when the cliché is being inked) and to the LOAD position (when the cliché is delivering its ink to the pad).

4. **INK/SKIVE.** A pair of "squeegees"; one of polymer which "Floods" the cliché with an excess of ink, the second of stainless steel which "skives" or scrapes away the excess ink leaving the grooves in the cliché filled. Low precision, inexpensive, but vulnerable to contamination outside clean-room facilities.
5. **PRINT.** An elastomeric pad attached to a spring-steel carrier which is in turn attached to the machine frame and which is placed in osculating contact with either cliché or ware by a cylindrical roller-actuator. The first stroke of the print-head extracts ink from the cliché, the second stroke deposits that ink on the ware. Motions of the actuator must be reproducible, but precise positioning of pad/actuator relative to cliché and ware is unnecessary so long as it is constant.

In this configuration of the printer, the slow step is loading the ware. The machine controller stops at the "LOAD" position (which is also the "extract ink from cliché" position) while loading is completed. Then, on manual signal, it cycles through the printing sequence shown schematically in Figure 6. The machine cycle time is limited by the manual loading time. If manual loading were as rapid as 2 sec, cycle time would be 15 sec. Practically, however, to assure even $\pm 20\mu$ position accuracy of the substrates using manual loading introduces an additional 2 sec. to a typical cycle. For certain applications, in particular for multilayer devices constrained to relatively low wiring density in the internal layers, this may be quite satisfactory. Maintaining high precision within a single layer would facilitate "fan-out" from semiconductor devices and the balance of the structure could be of relatively low precision.

B. Interlayer registry

It is possible to design for modest misalignments by, for example, adding "capture pads" to the ends of traces. Capture pads, enlarged pads at the ends of traces, are enlarged by an amount equal to the statistical uncertainty in stacking accuracy, so that worst-case misregistry will still lead to enough overlap to assure electrical continuity. In some instances, capture pad concepts are relatively economical of circuit area -- misalignments between resistors and the conductor terminals that connect them to the rest of the circuit can be easily accommodated. In certain kinds of high density wiring, particularly wiring of the "fan-out" from semiconductor bond pads to buried-layer structures, it may prove cost effective to increase wiring density by increasing the number of layers rather than by increasing the density within the buried layers. However, when there is significant discrepancy between line width and stacking accuracy, capture pads may become the limiting factor in wiring density. For manual loading, assuming placement of the cliché and each piece of substrate to $\pm 20\mu$, successive prints may be expected to be misaligned by $\pm 40\mu$ (rms sum of placement errors in two clichés and two placements of the ware). Hence the necessary capture pads would decrease the attainable wiring density by 37% relative to "perfect" alignment.

For the most demanding applications, manual loading should be replaced with robotic loading assisted by an optical alignment system. The manual system uses the edges

of cliché and substrate as reference "flats"; these are subject to dirt and wear, and live operators are subject to fatigue and inattention, hence high precision of loading cannot be assured. The optical/robotic system offered as an alternative would instead align with respect to fiducial marks on the back side of cliché and substrate; back side fiducial marks are far less vulnerable to dirt, optical location reduces wear and the robot reduces fatigue and inattention. Together, these improvements should improve stacking accuracy to better than $\pm 10 \mu$ while increasing loading rates. For the same example given above (two prints from two different clichés), the necessary capture pads would be only 20μ -- in other words no larger than the lines themselves. Note that this change in the Loader does not require change in any of the other modules. The reference stops on the Carrier become irrelevant, but the vacuum chucks would remain unchanged and the balance of the Printer, at constant cycle time, would yield more cycles per hour. Note that the trade-offs represented by improving precision at higher cost are device and design specific. Manual loading may be completely satisfactory for single-layer devices (cards providing interconnect between assembled components and connectors, for example). For multi-layer devices containing lots of interlayer vias, on the other hand, minimizing the number of vias may be the dominant factor in cost control and higher precision printing may be preferred at almost any cost.

C. Options

The alternative options in the Loading module have been discussed in some detail to elaborate the design philosophy. Like a "Chinese Menu", it should be possible to acquire a wide variety of capabilities in the Printer by "selecting one each from columns 1 through 5". Some options available for the other modules are:

1. If the user is doing or contemplating multilayer assembly, it is important to keep the top of the target workpiece co-planar with the cliché. Two versions of a basic modification to the **Carrier** will accomplish this. Each would be a Z-axis adjustment in the vacuum chuck for the substrate; one would be under operator (manual) control, the other would sense the pressure exerted on the pad actuator by contact with the substrate and adjust its height automatically to maintain a preset force range.
2. If the user requires higher speed or greater versatility from the **Transport** module (the rate controlling step if Loading is automated), the existing ball-screw and stepping motor can be replaced with precision optical position detection, a higher speed motor, and closed-loop control. This would reduce the cycle time by 1/3 or more.
3. The basic **Ink/skive** station is neither thermostatted, solvent-vapor controlled, or well protected from ambient contamination. If a user prefers longer unattended operation, highly intermittent operation, less severe constraints on workplace cleanliness, or "ultimate" control over ink rheology and "tack", a fully enclosed ink/skive environment is an available upgrade.
4. The basic machine runs under PLC supervision. If the user wants to vary the print cycle easily, wants to acquire SPC data on the fly, wants to be able to add control limits with audible or visual warnings, or in general wants a "friendly" operator interface, a **PC controller** using e. g. LabView will provide the interactive features.

D. Bonus

A fortuitous side effect of the precision alignment of cliché and substrate to the carrier merits closer examination. The same loading scheme is used for both cliché and substrate; manual loading is against hard "stops" in the Carrier and automatic loading is effected by a single vision system and carefully coordinated fiducial marks on the cliché and substrate respectively. This loading procedure will allow "set-up" of the printer in a single incremental cycle of the Printer. In other words, the Printer may be used to make a unique print on a unique substrate, changing each after each print, and yet retain 50% of the productivity that it would have for an extended run of a single image. Given the nature of the thick film business, the ability to make prototypes and short runs on production equipment with minimal penalties -- so-called "one up" manufacturing -- will prove to be quite attractive for many.

Three prototype machines have been built. The latest embodies the basic versions of each of the five modules. Many of the enhanced features proposed do not require invention. Vendors have been identified for major portions of each of the indicated upgrades, and the effort required to interface their subassemblies to the printer is modest.

IX. Characterization and Results

A. Test Evolution

Development of the pad printer was, in fact, development of a printing system -- ink, pad, cliché, mechanical components and environmental variables (temperature and air flow rate) all did or could influence the quality of the resulting prints. In the exact Pareto sense, the large problems were observed and corrected first, only to reveal more clearly the remaining less-large problems. As the problems themselves became smaller and more subtle, the tools of characterization necessarily became more precise and sophisticated. For example, as mentioned above, non-uniform pressure between the transfer pad and the ware led to broadening of fine printed lines. For the commercial printer, this could be detected "naked eye" because of the significant radial variation in pressure within a single print. In the later prototypes, the within-print variation in transfer pressure was small and difficult to observe, but the between-print variation due to setup inconsistencies remained and was observable after quantitative measurements of line width.

B. Qualitative

Certain entirely qualitative observations were highly valuable to the development of the inks. First, consider two narrow aspects of "stickiness" that apply critically to printing inks: "tack" is the tendency of an ink to stick to something else -- transfer pad or ware, for example -- while pituitous behavior results from the tendency of an ink to cohere to itself and form "strings" like stretched taffy when placed in tension. Tack of the ink must be controlled, and varied, within narrow limits because the ink must first attach readily to the transfer pad, leaving the cliché essentially bare, and then moments later must attach readily to the ware leaving the transfer pad bare. Clearly the cohesion of the ink must always exceed the smaller of the adhesion or tack stresses if this transfer is to occur. Equally clearly, if the cohesion of the ink fails to increase at the right rate, there is danger

of severe "tearing" or "stringing" of the ink. This is observed, most frequently, at the trailing edge of the pad footprint and produces a "ragged" print edge. A glaring example of the problem is shown in Figure 8. A more subtle version of the same problem is that the standard deviation of width of traces parallel to the direction of motion of the pad actuator are consistently lower than the same values for traces perpendicular to that direction.

Figure 8. Print showing pitted ink. Direction of withdrawal of pad left-to-right. Traces 25 μ nom.

C. Quantitative - Manual

The most important tool for physical characterization of prints was quantitative image analysis. The procedure was multi-step.

- Photograph the print. Typically a macro-photograph at $\sim 10\times$ was the best compromise between image precision and breadth of field. Also, typically, four, nine, or 16 photographs were required to "cover" the print area; cover, in this instance, meaning that readily recognizable reference marks on the print existed in at least two of the photographs and not meaning that all features in the print were photographed.
- Measure features on the photographs. The nominal measurement precision was $\pm 10\ \mu$ but operator skill and image quality combined to reduce this precision to $\pm 20\ \mu$ at best. This corresponded to $\pm 2\ \mu$ on the original print.
- When a feature is extensive in one direction only, make a large number of measurements of its dimensions in the orthogonal direction. Line widths, line spacing

and line separation could be measured repeatedly at small intervals, giving statistically independent estimates of the parameters.

- Determine mean and standard deviation for the measurements. Assuming that the measurements are truly independent, the mean is known to $n^{-1/2}$ times the uncertainty in an individual measurement -- for 9 observations the standard deviation of the mean is expected to be $\pm 7 \mu$ on the photo or $\pm 0.7 \mu$ on the print.
- Verify the assumption of independence by examining the calculated standard deviations, trends within data sets and consistency between measurements. A simple example: Ten line widths plus 9 line spacings must equal the (independent) distance measured across a meander pattern. Similarly, the distance from a "left edge" of a line to a "left edge" of a parallel line (i.e., the sum of one line plus one space) is insensitive to pressure-induced line broadening.
- Sum distances across multiple photographs to estimate longer measurements using the common fiducial. This permitted measurements on-print of features further apart than a single photographic field of view. Again error accumulation may be assumed to be RMS.

D. Automation

The procedure was satisfactory, but painfully slow. It was automated later in the program by scanning the photographs into a PC and "counting pixels" to determine distances. Scanning at 600 dpi produced a pixel of nominal dimensions 42μ referred to the photo or 4.2μ referred to the original print. But several times as many measurements of image features could be made in the same elapsed observational time and the operator contribution to error was smaller (i.e., the reproducibility of identical measurements was better). In short, the final precision of mean and standard deviation was unchanged and more detailed measurements were permitted.

Measurements of print thickness were extremely difficult. The substrate upon which prints were made had a typical surface roughness of 0.5μ RMS, so it contributed at least that uncertainty to mechanical measurements of print thickness -- a threshold error of $>15\%$ which was unacceptable. On the other hand, preparation of samples for optical or SEM measurement was greatly complicated by the fact that the substrate is very hard and surface-fired prints are comparatively soft. Ultimately, maximum confidence in estimates of print physical thickness was based on fracture through the substrate and print followed by SEM measurement as illustrated by Figure 9. Statistical averaging was not possible with this sample preparation technique, so the uniformity of print thickness (if not the absolute value) was estimated from measurements of sheet resistivity. In the late stages of the development, the uniformity of line width was sufficiently good that essentially all variation in sheet resistivity could be ascribed to variation in print thickness.

Figure 9, SEM photograph of fracture through substrate and print.
Average print thickness 2.8μ .

Three kinds of variability are of concern in printing:

1. variability within a single feature is an estimate of the probability that a given trace will contain an open or will short to its neighbor.
2. variation across a single print is an estimate of distortions due to printing mechanics (if the variation is systematic) or of uncertainties of manufacture of cliché (if random, but reproducible) or of inability to make the measurements themselves (if random and not reproducible).
3. variation between prints is a measure of machine mechanics and, of course, a crucial measurement of the ability to align prints and other physical features well enough to make real devices.

E. Status

Within a single feature or array of similar features -- simulated electrodes and traces of the various sample patterns -- the standard deviation of print edges is extraordinarily small. As noted above, the measurement capability of the techniques developed for this program was $\pm 0.7\mu$ based upon 20 measurements using the image analysis system or 10 measurements using the photo-mechanical measurements. The variation in trace widths observed for all 25μ and 50μ traces (the most frequently measured traces) after the ink development was essentially complete and even before the final machine prototype was available was of the order $\pm 2\mu$, less than 3σ the measurement accuracy itself. Recalling that these are 1σ values, this implies that a 6σ

line-width (probability of an open less than 1×10^{-5}) need only be 12μ wide. In turn, this provides great confidence in 25μ lines -- the target value for the program

F. Stochastic Errors

The actual number of open traces was significantly higher than 1×10^{-5} and most of these open traces were visible to the naked eye. The difference between small-scale prediction and large-scale observations is directly traceable to cleanliness. The environment in which substrates were stored and in which printing occurred was normal laboratory space, clean-room Class 100,000 or poorer. Again recalling the discussion of "tack", minute amounts of surface contamination from moisture, air-borne debris, and the like were able to produce non-printed areas, occasionally of considerable size. One should expect that careful attention to contamination on the same scale as the print features ($3\text{--}30\mu$) will be required to get consistent yields. In related experience, it appears that Class 1000 clean-room facilities are quite satisfactory.

G. Systematic Errors

There is an additional consistent error in single print observations. Traces are wider than their image in the cliché and therefore spaces are somewhat narrower than their image. This variation is consistent for isolated traces and for sets of identical traces (such as the meander patterns that are frequently represented in test prints. The amount by which trace width exceeds cliché groove width increases with pressure between pad and ware and varies from 3μ at the minimum pressure which gives good prints to several times that at high interface pressures. It has not been possible to quantify this variation because the early prototype machines did not permit precise setup or precise determination of the contact pressure between pad and cliché or ware. This difficulty has been addressed in the most recent prototype machine and there is every reason to believe that the "printout" of ink can be made sufficiently reproducible that it can be incorporated into the design of the cliché; i. e., to obtain 25μ lines and spaces put 22μ lines on 50μ centers. A different aspect of this problem may be more difficult to design around. When a trace is near to and parallel to the edge of a large feature such as an electrode it appears that the large-area feature "shelters" the adjacent trace from the total applied pressure. Obviously this effect is smallest when total pressures are small but it represents a possible complication of the design rules.

H. Error Accumulation in Plane

Variation across a print is difficult to measure, as noted above, because it must "sum" a number of individual measurements, each with some uncertainty. Given that a single photomicrograph (at $10\times$) observes an area of print that is nominally 8×11 mm and further given the need to replicate features in adjacent photomicrographs to assure continuity of measurement, it is apparent that the long diagonal of a 100 mm print field will require summing up to 15 measurements. Even if the errors are independent of one another and therefore add as RMS, this means that individual measurement errors of $\pm 1\text{--}3 \mu$ can result in cumulative errors of $4\text{--}12\mu$. The higher numbers result when features cannot be measured large numbers of times and averaged; this is particularly true for diagonal measurements where multiple measurement opportunities simply don't exist.

There is an additional complication. It can be assumed that CAD files do not accumulate errors, but it cannot be assumed that the techniques for printing a photopositive from the CAD file or the procedures for converting that photopositive to a cliché are free of systematic errors. For example, a few degrees of temperature change will permit tens of microns of thermal expansion in a polymer photopositive. While many of these sources of error don't exist for the laser-machined clichés, the expense of producing large laser-machined clichés is prohibitive. Single prints containing image elements more than 100 mm apart have been uniformly printed from polymer clichés with inherently greater random and systematic errors. To approximate the consequences of these errors, both the cliché and the print was measured and the differences were estimated. Again, adding errors RMS, the final confidence in measurement was $\pm 6-17 \mu$. The observed errors in every case were comparable (to 60% confidence) to the standard deviations in the measurements.

I. Stacking Errors

Quantitative data on the third critical kind of printing error are not available. These data are being generated in two steps to distinguish between errors of machine transport reproducibility and errors of loading accuracy. In the first experiments, a single cliché is loaded and retained in the printer and a single substrate is loaded, printed, removed, fired, reloaded and reprinted. Because fired prints are "shiny" and dried-but-not-fired prints are black, the mis-registry due to two independent loading of the target substrate, plus any uncertainty in the transport system, can be determine in both X and Y by examining the edges of the print features. Errors due to positioning of the cliché are eliminated. In the second experiment, substrates which have been previously printed and fired with conductor patterns and which are precisely characterized for random and systematic error will be printed with a resistor formulation; the resistor pattern allows both random and systematic errors in registry to be measured physically and the resistors can be probed electrically to determine the variation in print thickness as well. These efforts are a part of the Commercialization effort which is continuing and will be described in greater detail below.

J. Electrical Measurements

The primary tool for electrical characterization was measured resistance. This is an easy measurement -- fast, precise, largely free of sampling errors. Nevertheless, when probing a fired resistor ink, there is some uncertainty about contact effects. In the early measurements, this was accommodated by making multiple measurements of a single trace, throwing out markedly high readings under the assumption that they represented a contact problem, and averaging the remaining readings. In later measurements, the contact pads were themselves tinned with high conductivity material (usually solder, sometimes an organic bonded silver paste) which was sufficiently conductive that there were no markedly high readings. Particularly when temperature-dependent resistance was of concern, as in the resistor formulations, the latter method allowed "permanent" contact that withstood temperature excursions. Electrical measurements were able to clarify certain physical measurements. For example, comparison of electrical and physical measurements under variable pad pressure strongly indicated that the volume of ink being

deposited was essentially constant. Trace resistance was essentially independent of trace width while trace sheet resistivity increased proportionately to trace width, suggesting that the current-carrying cross-section of the trace was of constant area.

Measurements of the electrical resistivity of fired traces also confirmed that considerable latitude was permissible in the Printer set-up. Prints made from the same ink days and months apart varied by less than $\pm 5\%$ in trace resistance. In the same fashion, the ratio of observed trace resistance to the value calculated from the bulk resistivity of the alloys used (with "rule of thumb" allowances for retained glass frit) was constant for 5-40% Pd in Ag and for 5-15% frit in several of the alloys. This is quite comparable to, perhaps superior to, common industry experience in thick film screen printing. A typical SEM photomicrograph of a fired trace is presented in Figure 10. The darker "holes" in the metal are indeed holes and the surface

Figure 10. SEM photograph of fired electrode. Reference mark is 10 μ .

roughness is apparent, so it is obvious that the measured resistivity should be higher than a theoretical value based on dense planar foil.

A selection of the "raw data" that these observations are based upon is reproduced in the following Table.

No.	pigment	firing T, °C	mΩ/□
1H12D	70Ag/30Pd	1100	100±8
1H17E2	70Ag/30Pd, 5%frit	850	140±9
1H17B	70Ag/30Pd	850	120±9
1H21B	90Ag/10Pd, 5%frit	850	50±10
1H20C	95RuO ₂ / 5 frit	850	15000±2000
1H28F	85RuO ₂ / 15 frit	850	25000±2000
1H31G	70RuO ₂ / 30 frit	850	30000±2000

Table I. Sheet resistivities of assorted inks.

A number of qualitative observations continue to be made, primarily to establish the compatibility of Pad Printed features with the balance of the thick film assembly process. Various adhesive bonding and soldering operations have been performed without incident. This is reassuring, because solder is known to attack precious metal films and these traces are deliberately thin. One attempt was made at laser-scribing a resistor formulation and it was unsuccessful. The most probable explanation for this observation was that the laser was a He(Ne) type with wavelength significantly longer than the thickness of the target resistor and the laser technician was accustomed to trimming only after applying a glaze overcoat several tens of microns thick. This exercise will be repeated with a fully glazed resistor soon. Samples have been supplied for studies of wire-bonding at NIST (courtesy of Dr. George Harman). He was able to make good bonds in thick areas of prints, but found that areas thinner than ~1.5μ could not be bonded satisfactorily. Given that the printed pads were in a Pd/Ag alloy containing a rather large amount of frit, these results are not discouraging -- and no Au inks have yet been formulated.

X. Commercialization

This entire development has been followed eagerly by many of the commercial thick film manufacturers. Sometimes their interest has been overwhelming -- significant encouragement to print flat panel displays with 50μ lines on 240μ centers over a field as much as 300 mm wide. While it would be nice to be able to respond to such interest, that goal is premature.

On the other hand, four domestic and two offshore companies have been sufficiently interested in the efforts to send engineers to "kick the tires", to spend significant time and effort in preliminary evaluations, to suggest tentative specifications, and to propose test patterns and the like. In aggregate, their direct contribution represented over 2% of total program expense during the active portion of the program and now -- as the risk of failure is reduced -- is growing rapidly.

A number of "progress reports" were presented to DARPA and National audiences during the Program ^{6,7,8}. (These are Appended to the present report.) The reception was fair to excellent, depending on the venue, and a fairly extensive mailing list has been established of potential purchasers and, in some cases, of end users who require capabilities that only the Pad Printer can deliver. In this latter category are a number of military "consumers" with program management responsibility. At least two Trade magazines have offered to feature the printer "when you are ready to market it vigorously". The current prototype printer is still, by design, "naked" of the cosmetic sheet metal that is appropriate for sales brochures and trade shows, so it seems premature to pursue this opportunity for a little longer.

The third prototype printer is operational at MRA Laboratories. This version was extensively modified by Abacus Automation to make it more accessible, and to assure that it would be more spatially and temporally reproducible. It is deliberately a "minimal" version of the machine -- relatively slow and only as precise as manual loading permits. The controller is housed in an oversize box adjacent to the printer and no effort has been made to hide the cables and hoses. It does, however, execute all the unit operations correctly and we have been able to expand the workspace for evaluation to somewhat greater than 100x150 mm in this iteration of the machine. A small number of photographs are included as Figures 11 and 12. They may be 'busy' for casual examination, but can be interpreted by noting that they are a "mirror" image of the schematics in Figure 7.

The significant, continuing, effort to commercialize the Pad Printer is focused at this time on an extensive joint development effort with an existing customer for other services of MRA Laboratories. This customer, in two different operating divisions (both of whom are participants in the effort) presently operates in excess of 40 silk-screen printers and in many instances is operating them at the extreme limits of their capability. His primary product is discrete devices processed in modest arrays; his obvious opportunity is to shrink the size of the individual devices so as to yield more devices per array. The smaller device size actually commands a premium from his customer, so he can "win" twice if the size can be reduced without negative impact on yields. Because he is working very near to the state of the art, his existing resistor inks are optimized for "fine-line" printing. They do not meet the tentative specifications established for 25 μ lines and spaces in this program, but they appear to be suitable for 50 μ lines and spaces -- still a nearly 3x improvement in his process. As noted above, for a variety of reasons, truly fine-line printing is not nearly so necessary for resistors as for conductors and even 100 μ resistors of excellent reproducibility will be a contribution to the state of the art. If these resistor inks can be adapted, they would in all probability provide an "instant" catalog of resistors to anyone interested in using the Pad Printer. Part of the terms of the joint development are free license to manufacture such inks for sale to third-party customers.

In preliminary work it has been established, as expected, that the existing formulations are not satisfactory for pad printing. By the time the existing inks could be diluted enough to be printable, they had such a low solids content that the prints, while cosmetically satisfactory, were totally unacceptable electrically -- generally open circuits. In phase II of the development, we have used the inorganic pigments from the customer

Figure 11: Prototype Pad Printer

Figure 12a: Prototype Pad Printer Detail: Flood and Skive

Figure 12b: Prototype Pad Printer Detail: Pad and Actuator

inks -- extracted from the inks and supplied as virgin powders -- and dispersed them in our preferred organic vehicle system. As expected, this yields inks which print satisfactorily and give cosmetically good prints. We cannot report electrical results from this effort at this time.

XI. Deviation from Schedule

The original plan of the development was followed surprisingly closely for the first 19+ months of the planned 24 month program. In fact, during that period only one revision of the original Gantt Chart was published. At the end of the first year's effort, a revised Gantt Chart was released with no change in anticipated effort or proposed milestones. It was revised to suppress detail in completed Tasks and to elaborate the forecast of current and pending Tasks.

This is not to say that planning was perfect. One technical hurdle proved far more difficult than anticipated -- identifying a competent, relatively inexpensive, vendor of clichés. The extra effort that this required was partially offset by the comparative ease of designing and fabricating the first of the prototype printers. One non-technical hurdle was also significant -- effective communication between the participants and with the sponsors required a great deal more travel than was anticipated. The consortium members anticipated quarterly meetings "on site" at one or another of the development facilities. Specifically, we expected both to inform the sponsor of program status and to plan and coordinate the next steps in the work in each single trip. In practice, the majority of meeting with sponsors were held in Washington, and the necessary coordination meetings could not be held without essentially doubling the travel budget. This necessary reallocation of development funds was understood and accepted by the sponsors and absorbed into a fixed budget. For the first roughly 80% of the program, then, performance was both Temporally and Fiscally satisfactory.

In October of 1996 the situation began to deteriorate and by December of that year the ability of the consortium to complete the program was jeopardized. In that period, L&L Inc. effectively ceased to exist. The details are the raw material of soap operas, but the consequences have been absorbed. The situation was handled in two steps. First, with the full cooperation of L&L, Inc., a portion of the funds allocated to them and a portion of the funds they were to contribute were sequestered to allow completion of their portion of the effort. Second, the remaining consortium members began a careful search for a company to provide the level of competence and effort represented by L&L. The parameters of that search were:

- Skill. An understanding of precision machines, control technology, good vendor relations for subassemblies, excellent design and fabrication capabilities.
- Modest size. Big enough to be capable, small enough to view the opportunity as significant.
- Well known to ourselves. Build on an existing track record of cooperation.
- Nearby. The physical separation between Massachusetts and South Carolina had proved to be a complicating factor in the original development. Particularly as the

"pieces" began coming together (and as the consortium moved to selling an integrated system), the shortest possible lines of communication seemed desirable.

The search fairly quickly narrowed to two candidates, each founded by former Sprague Electric Company employees and located within a 50 mile radius of MRA Laboratories. Both MRA Laboratories and MultiLythics have long tenure within the Sprague Electric Company, so these were candidates very well known to us. Both easily met the target "skill" parameters. The principle difference between them was size. Abacus Automation, in Bennington, VT was the larger, more diversified, arguably more capable company. The other candidate, in Pittsfield, MA was somewhat less capable, but arguably more strongly attracted to the task -- or less distracted by other commitments.

Abacus Automation has joined us at two levels of commitment. First, to complete the third prototype pad printer, effectively completing the Program supported by DARPA. Second, to act as equipment vendor to the consortium going forward. In other words, to manufacture Pad Printers to customer specifications in any of the multiple configurations suggested by the "Chinese Menu" outlined above, and to assist in identifying those customers and negotiating cost and performance agreements with them.

The net result of these changes is mixed. The consortium lost valuable time in completing the Program, although customers have been patient and there does not seem to have been great loss of "momentum" in the marketplace. The team that is now assembled is stronger than the initial consortium and the geographic proximity of the two manufacturing entities makes marketing the product more effective. The costs to the participants were somewhat increased and the returns somewhat delayed, so the profitability of the venture is reduced according to the usual accounting conventions. However, the prospect for profitability remains bright and, with the continuing support of customers, commercialization seems assured.

XII. Financial Summary

The delays in completing the program described above were not accompanied by cost over-runs. Alternately, the incremental costs which were incurred were borne by the participants and by our commercial customers. The sponsors patience during the delay contributed significantly to managing the dislocation and no incremental funding was required.

In keeping with the interim progress reports, the final financial summary is attached in DOE-suggested format as Figure 11.

XIII. Acknowledgements

The financial support of DARPA was certainly not trivial. However, equally important was the keen technical insight, the penetrating questions, and the careful "cross-fertilization" provided to this Program by Dr. James Murphy of DARPA and Mr. John Tribou of DOE Albuquerque Operations. Each functioned as an "unpaid volunteer" and their contribution is greatly appreciated. Additionally, Dr. George Harmon of NIST provided topical evaluation of wire-bonding compatibility of the printed conductors, focused insight into quantitative measures of print quality, and editorial review of interim

and final reports sharpened by his own extensive writing experience. Mr. John Chase of the Bourns Company provided preliminary data on laser trimming of pad-printed resistors, provided expert consultation in the formulation of preliminary specifications for the printer, and has been a constant source of inspiration and motivation as the surrogate for all customers. Mr. Darnall Burks paid a key role in the development of the Printer and continues, as customer and friend, to assist in its commercialization.

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