Laser Machining of Thin Films and Integrated Circuits

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The feasibility of using the YAG laser as a tool to thermally machine integrated circuits has been studied. Results suggest that defining the resistor geometry, trimming the resistors to value, fabricating gap capacitors, and defining interconnecting circuitry might be performed by such a laser.

Pattern generation by laser machining has been demonstrated on various thin and electroplated films. Vaporized lines (gaps) are readily attainable as fine as 0.25 mil in thin films and 0.4 mil in plated films. Much thinner lines may be obtained under particularly well-controlled conditions. These films may be removed with minimum effect to the substrate surface. The heat-affected region of the substrate may be confined to less than one film thickness. Better laser output control and shorter pulse widths will diminish this thickness.

Gap capacitors have been made on sapphire substrates with capacitance approaching 20 pf in 0.04 square inches, and experiments suggest improvements.

Tantalum films may be shaped to resistor geometries and trimmed to tolerance by removing metal or by oxidizing the resistive film with the laser. Resistors usually can be trimmed to tolerances of less than ±0.1 per cent.

With further development it might be possible to combine these laser machining processes into a single-step, automated fabricating procedure for certain types of integrated circuits. We review some of the technical aspects of this and discuss using Q-spoiled YAG lasers to directly machine masks for photoetching.

I. INTRODUCTION

The steps to fabricate thin film passive elements and interconnecting circuitry on hard substrates are well documented.[1,2] These procedures, defining resistor geometry and interconnecting circuitry, resistor trimming to value, and capacitor fabrication, are the essential steps for producing precise integrated circuits. It is our intention to show that a laser can be used to vaporize, in a controlled manner, thin film structures, and that it therefore might be capable of supplementing or performing these four processes; or it might be used to supplement photolithography by directly machining thin film masks for making circuits by photochemical methods.

We studied methods for performing these steps with a continuous neodymium doped yttrium-aluminum-garnet (YAℓG:Nd or YAG) laser. Laboratory work has demonstrated the feasibility of fabricating circuit building blocks and eliminating many steps for film structures which are common to tantalum integrated circuits; that is, circuits in which the resistive films are compounds of tantalum. Similar techniques will be applicable to other types of circuits.

Tantalum thin film resistors have been shaped and trimmed to value with a laser beam. A controlled laser has removed various combinations of thin films from substrates without adverse effects to the substrates. Tantalum films have been thermally oxidized with the YAG laser as the heat source. Controlled parasitic or gap capacitors have been made with specific capacitance up to 4.5×10^{-4} pf per square mil by laser machining narrow lines across thin films.

The YAG laser has demonstrated considerable potential as a thin film machining tool. The simplicity of operating and controlling the device, and the characteristics of its output beam render it particularly well suited to this application.

II. GENERAL CONSIDERATIONS

2.1 *Characteristics of Lasers as Fabricating Tools*

The utility of a laser as a tool for fabricating thin film circuits results primarily from the spectral purity and degree of collimation of the laser light. These characteristics allow the beam to be focused to a very fine and intense spot. The high heat flux which occurs when the light is absorbed by the target material, and the sharp definition and localized nature of the working region allow heating, melting, or vaporizing minute amounts of material, with minimum effect to adjacent material or components.

Among other useful characteristics of light as a working tool is its small absorption depth in metallic materials. This property renders the laser particularly applicable to operating on thin materials such as films without damaging the substrate or material beneath the film. In addition, energy may be transferred to the workpiece through an optically transparent material or atmosphere, and without physical contact with the workpiece. Encapsulated or otherwise inaccessible parts may be machined, and working regions may be kept free of contamination which might result from contact with a tool. References 3 and 4 give more detailed discussion of the suitability of lasers for fabrication.

Many types of lasers have been shown to be applicable in processes related to thin-film circuit fabrication. Pulsed lasers have been used to vaporize slots and lines in metallic targets[5] and have been included in an experimental automated procedure for trimming thin-film resistors.[6] Pulse-pumped He-Ne gas lasers have been used to scribe lines on metals.[7] Reported linewidths are 12.5 microns. Ionized argon lasers operating at one-half watt cw output have been used to scribe lines as fine as 10 microns in iron-nickel films deposited on glass.[8]

The neodymium-doped yttrium-aluminum garnet (YAG) laser discussed by Geusic and others,[9–11] is particularly well suited to thin-film fabrication because of its good combination of such characteristics as the adequate intensity, stability, and optical quality of the output beam, and its simple and compact design. Such YAG lasers may be operated continuously at about 1 watt output, or may be repetitively Q-switched by rotating the rear reflector. The Q-switched output is a continuous train of pulses with peak power exceeding 1 kw, and pulse duration about 200 ns when the repetition rate is 400 cps. Both types of operation may be obtained by using as a pump source an inexpensive lamp powered directly from line current. In both cases the laser may be adjusted to oscillate in a sufficiently low order mode that the output beam may be focused conveniently to the fine spot needed for precise thin-film machining.

2.2 *Machining Thin Films*

The processes that we studied, except thermal oxidation, use the laser's ability to vaporize material. It is desirable, therefore, to discuss briefly a few of the parameters and phenomena of material removal by laser. Cohen and Epperson give more detail.[3]

We notice first that it is the optical power density in the focused spot rather than the laser power output, itself, that determines the suitability of a laser for removing material. Greater power densities often may be obtained from a laser that oscillates in a low order mode, than from a higher-powered multimoded device. For the useful case of a laser oscillating in the fundamental Gaussian mode, the minimum focal spot radius, w_f, may be determined from the relationship. (See Ref. 3.)

$$\frac{1}{w_f^2} = \frac{1}{w_0^2}\left(1 - \frac{(z_0 + d)}{f}\right) + \frac{1}{(f\theta)^2} \tag{1}$$

where, f is the focal length of a lens with sufficiently great aperture to admit the entire beam, w_0 and z_0 are parameters which depend upon laser cavity configuration, d represents the distance of the focusing lens from the cavity, and θ is the far-field beam divergence angle. In many metal-working applications, including the one we are discussing, the lens is sufficiently far removed from the laser output reflector that equation 1 becomes

$$\lim_{[f/(z_0+d)]\to 0} w_f = \frac{\lambda f}{\pi w} \tag{2}$$

where w is the radius of the beam as it enters the lens. Equation 2 predicts, therefore, that spot sizes of the order of wavelength, λ, may be obtained with lenses having small f numbers (that is, small ratios of focal length to aperture).

The size of the affected zone in the target material will depend on the thermal properties of that material as well as the optical spot size and the intensity distribution across the spot. Edge definition of the affected zone depends primarily on thermal properties of the target and the duration of exposure. Metals with high thermal diffusivity and a large difference between melting and vaporizing temperatures, such as gold and copper, tend to develop a lip formed by molten metal around the region from which material was removed. The lip may be minimized by using a very short exposure such as that which might result from operating the laser in the Q-switched mode.

The use of Q-switched output also is desirable to minimize thermal damage to the substrate. Damage results both from heat conducted from the film into the substrate, and from direct impingement of the focused laser light on the substrate after the film has been removed. Using laser pulses of high peak power and short duration substantially decreases both effects.[3]

Many metals reflect an appreciable portion of the incident laser light. Such metals might need much higher laser output levels than nonreflecting materials. In most laser micrometalworking processes, the surface remains solid and reflecting for only a small portion of the laser pulse duration. The reflectance of the surface may decrease abruptly when it melts or reacts with its atmosphere, and subsequent absorption will occur with greater efficiency. The initial laser output, however, must be sufficient to break down the surface.

2.3 *Experimental Apparatus*

Figs. 1 and 2 show the apparatus used in our experiments. The YAG laser was Q-switched by rotating the rear reflector at 400 hertz. The output pulse parameters at the rated voltage of the pump lamp (120 V) were about 1 kW peak power and 200ns duration at the half power point. Output, at 1.06 micron wavelength, was monitored by means of a photomultiplier tube behind the cavity, and the photomultplier frequently was used in conjunction with a thermopile which measured the mean power of the output beam, so that the peak power could be calculated. The laser output was attenuated by neutral density filters. Laser mode pattern was observed by means of an image converter tube, and the laser cavity was adjusted periodically so that most of the output was contained in the fundamental mode.

An x-y-z micropositioner was used to focus and move the workpiece. For applications such as line scribing, in which the work is moved across the beam, one of the micrometer barrels is rotated by means of an hydraulic drive coupled to a gear and belt mechanism. A wide range of continuously-variable speed was available. The maximum

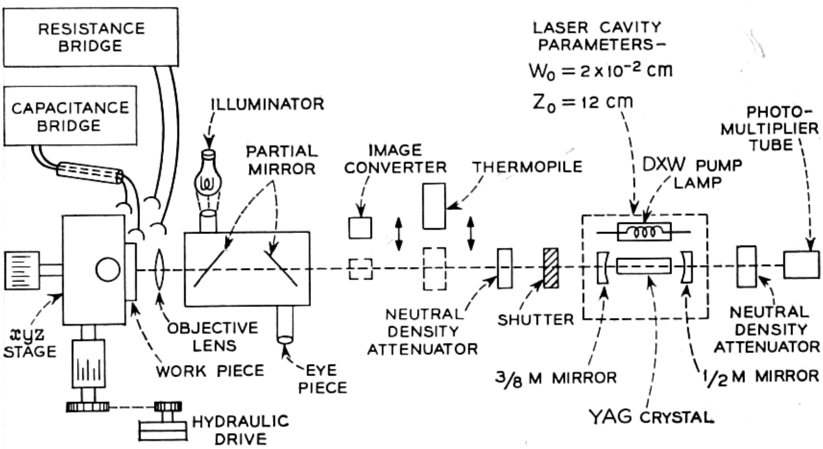


Fig. 1 — Schematic diagram of laser machining apparatus.

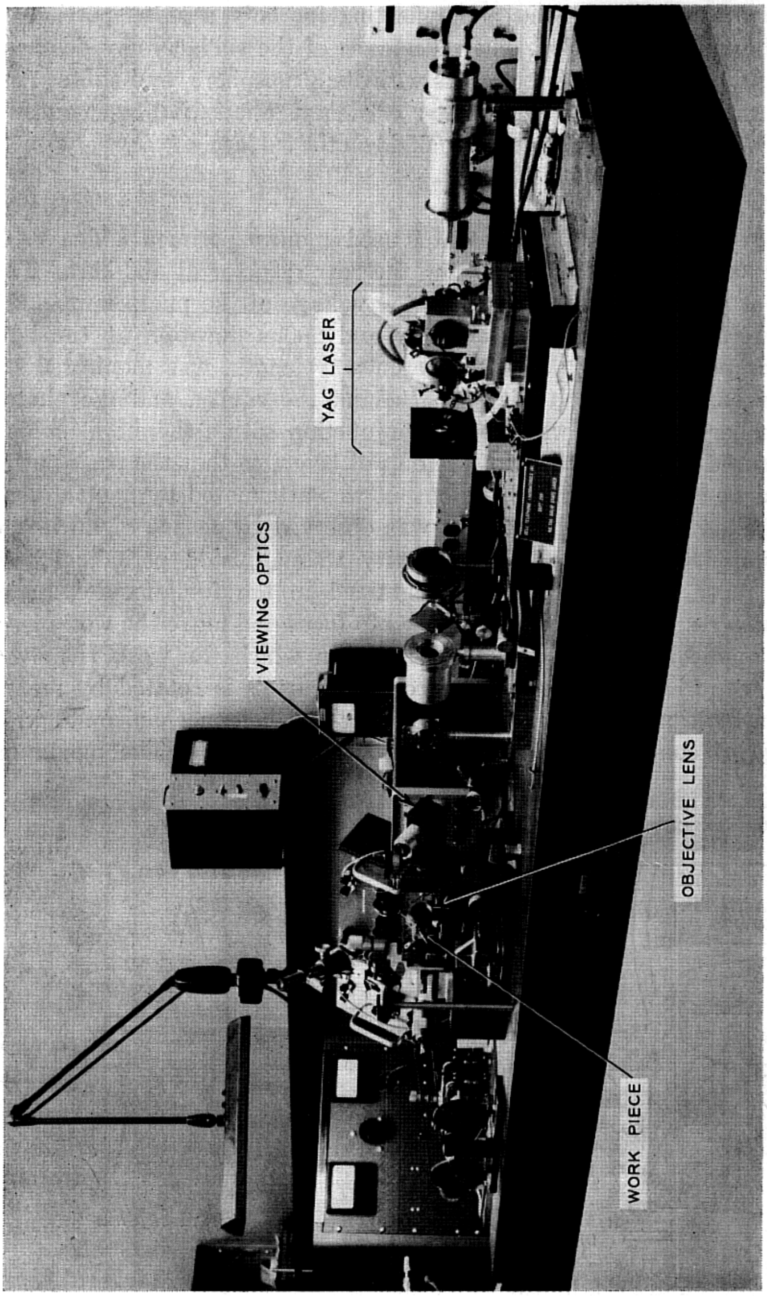


Fig. 2 — Laser machining apparatus.

permissible sweep speed, however, was dependent upon the diameter of the focal spot and the stability of the laser output. With excessive sweep speed, successive laser pulses did not overlap, causing scalloping at the edge of the line. Speeds of 0.1 inch per second were permissible with 0.0002-inch gaps, and correspondingly lower speeds were required with smaller gaps. Working atmosphere generally was air, although limited tests suggested that somewhat better edge definition is possible in oxygen-rich environment.

The viewing and focusing device consisted of two partial mirrors and an eyepiece mounted on a traverse mechanism, and a separately-mounted microscope objective. Objectives with 23 mm focal length (10X) were used for most of the applications studies associated with direct machining of tantalum integrated circuits, and lenses with focal length as short as 4 mm (approximately 70X) were studied for thin-film mask-making application.

The 23 mm objective was a particularly good lens for general-purpose work. Its depth of focus was sufficiently great (approximately ± 0.001 inch) that fine lines of appreciable length (greater than 0.5 inch) usually could be scribed with good uniformity on nonuniform surfaces such as that of a glazed alumina substrate without elaborate alignment of the workpiece. The spot diameter, $2\ w_f$, calculated from equation 1 and the parameters appearing in Fig. 1, was about 8 microns (about 0.0003 inch) for this lens. Increasing the strength of the objective to about 40X will decrease the calculated spot size to about 2 microns, but the severe loss of depth of focus restricts use of such lenses to very flat and well-aligned targets. Such lenses with short working distances also necessitate careful attention to laser output intensity in order to prevent lens damage due to the laser plume of vaporized material.

The apparatus described has been used to vaporize spots and scribe lines in a wide variety of thin-film structures. Figs. 3 through 5 show some of the general characteristics of such lines.

Figure 3 indicates the effect of laser beam intensity and stage sweep speed on width and definition of lines vaporized in a gold thin film (approximately 3000 Å) on sapphire substrate and a nichrome film (2000 Å) on quartz. An 8 mm lens was used to scribe the gold film and a 4 mm lens was used for the nichrome. The finest lines were about 0.00025 inch wide for the gold and 0.0001 inch for the nichrome. Such gaps generally contain no metallic debris, as evidenced by the very low electrical conductance that is measured across them.[3]

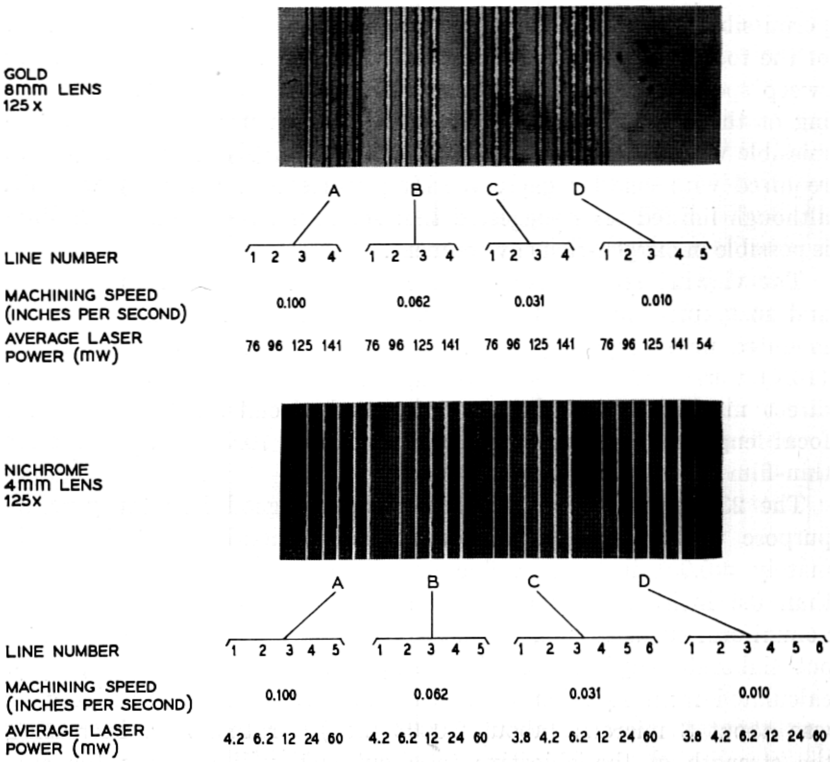


Fig. 3 — Effect of machining parameters on lines machined in 3000 Å gold film on sapphire and 2000 Å nichrome film on quartz.

Lines as fine as 0.00004 inch (1.0 micron) have been scribed in tantalum nitride, titanium, and nichrome films.

It has been shown that for thin film samples similar to those shown in Fig. 3, the extent of damage to the sapphire substrate may be minimized by proper control of power density and sweep speed.[3] Fig. 4, representing a typical cross section through such a sample, indicates that the extent of the affected zone may be limited to a depth approximately equal to the film thickness. Recent results have shown that some metal films may be removed with no substrate damage observable by optical means.

Fig. 4 also suggests the presence of a small gold lip bounding the laser-machined gap. The size and nonuniformity of the lip, and the depth of the thermally affected zone in the substrate increase as the film thickness is increased. Fig. 5 shows typical depth of penetration into the sapphire when the gold thin film is plated with approximately 0.3 mil of copper and then 0.01 of gold. Although gaps as narrow as 0.00020 inch have been machined in such films with a 23 mm lens, gaps smaller than the film thickness require precise control of laser and stage parameters. The lateral extent of the heat-affected zone resulting from thermal conduction in YAG laser-machined thick films often is the same as the film thickness.

Results similar to these have been obtained when the substrate material is glazed alumina, quartz, or silicon rather than sapphire, although the body of data for these materials is not nearly so large as it is for sapphire. Damage to the surface, apparently caused by melting, is confined to a depth less than the film thickness. Cracking of the glaze in the vicinity of the working zone has not been observed when laser parameters have been adjusted properly.

III. DIRECT MACHINING OF TANTALUM INTEGRATED CIRCUITS

3.1 *Gap Capacitors*

3.1.1 *Characteristics*

Interelectrode effects normally are present in miniaturized or high density integrated circuits. However, these parasitic or stray capaci-

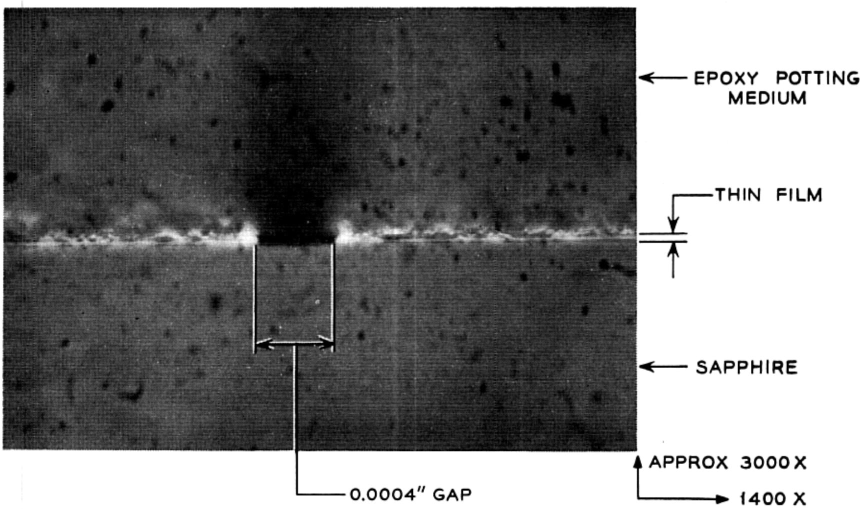


Fig. 4 — Cross section through gap machined in 3000 Å gold film showing the affected zone in the sapphire substrate.

tances usually are minimized by judicious spacing or isolating the components. These parasitics, gap capacitors as we call them in this article, can be produced with values high enough for use as discrete circuit elements by varying the spacing and length of the coupling electrodes, and the dielectric constant of the surrounding media.

Kaiser and Castro have calculated the interelectrode effects between two thin film conductors deposited on a substrate.[12] The calculations were directed at predicting parasitic capacitances between parallel conductors on substrates of various dielectric constants. The analysis was based on a model of two parallel conductors a distance d apart, of equal width l, on the same side of a substrate with dielectric constant k, of finite substrate thickness t, and of infinite extent. It has been assumed that the dielectric constant of the environment is negligible compared with that of the substrate. Fig. 6 presents, for various d/t and l/t ratios, calculations based upon this analysis.

Fig. 6 shows experimental data for some gap capacitors fabricated in the laboratory by means of a Q-switched YAG laser. Gap width was varied from 0.0005 to 0.025 inch for thin chrome-gold films on 0.025 inch thick barium titanate substrates (dielectric constant approximately 500), and 0.0003 to 0.015 inch for tantalum-chrome-gold thin film composite on 0.03 inch sapphire. In the case of the high dielectric substrate, agreement with numerical calculations is best for the larger gaps. Behavior for the fine gaps probably is affected by the granular and nonuniform nature of the substrate, and further study

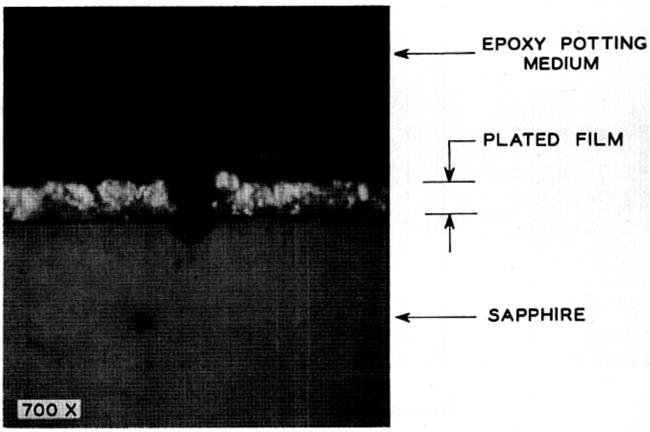


Fig. 5 — Cross section through gap machined in plated thin film showing the affected zone in the sapphire substrate.

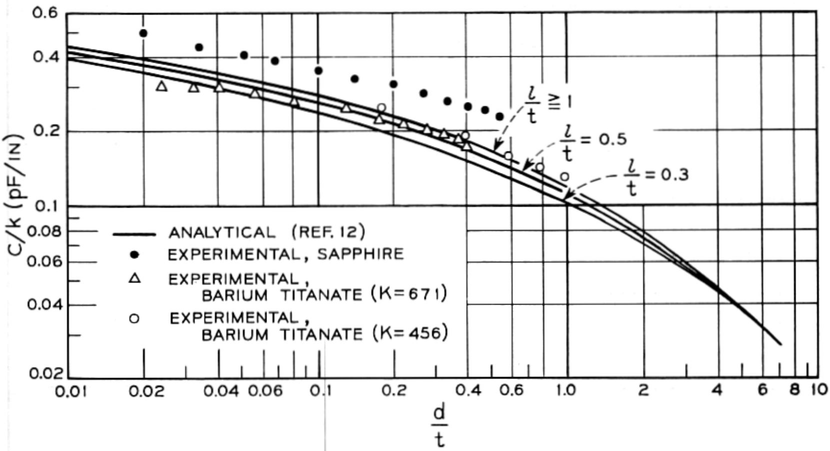


Fig. 6 — Capacitance of gap capacitors as a function of gap width. Comparison of analytical and experimental results.

is necessary. The shape of the curve for sapphire is similar to that predicted by the analytical model. The displacement between the curves may be explained by considering the fringing capacitance through the environment.

3.1.2 *Laser Fabrication*

A Q-switched YAG laser was used to machine fine lines in thin film conductors to form the gap capacitors. The effects of gap width, line length and geometry have been investigated. Most of the data were obtained with gap capacitors on single crystal polished sapphire substrates. Limited data also have been obtained for other substrate materials.

Fig. 7 demonstrates the linear relationship that has been observed between capacitance and gap length. There is no observed effect of bending the cut into a serpentine configuration until, as will be shown later, the parallel legs become sufficiently closely spaced. These results suggest that there is no significant contribution due to the field concentration at the corners, since such an effect would cause a deviation from linearity.

Most of the data in Fig. 7 were taken on tantalum-chrome-gold thin film composites on sapphire. Some data also are included for gaps machined in 0.3 mil thick copper-plated conductors. Gap width in

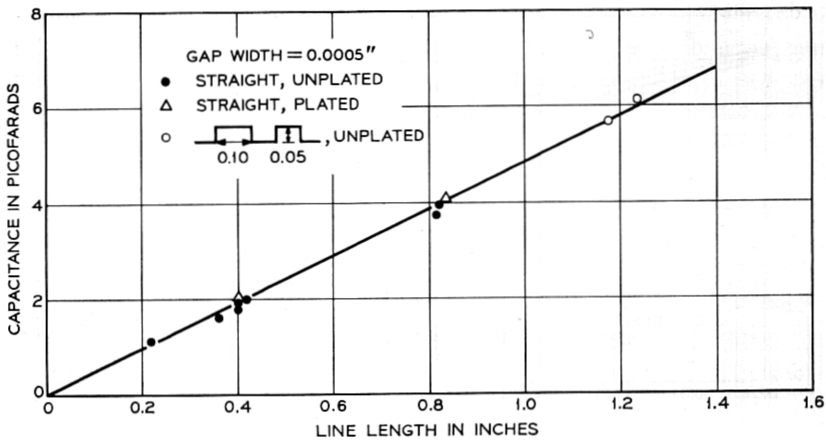


Fig. 7 — Capacitance of gap capacitors as a function of gap length.

both cases was 0.5 mil. The plated films appear to produce capacitance values similar to those for unplated thin films.

The response of gap capacitors to frequency was determined by measuring a gap capacitor at frequencies to 4 GHz. A plated 0.5 mil wide gap capacitor cut in a plated 50 ohm transmission line on an alumina substrate (Fig. 8) was measured with the following results:

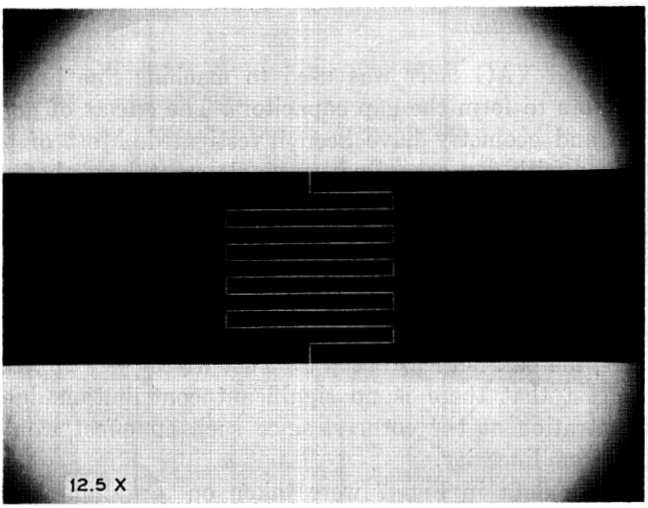


Fig. 8 — Gap capacitor laser machined in plated 50 ohm transmission line on glazed alumina substrate.

At frequencies of 465 kHz, 1 MHz, 3 GHz, and 4 GHz, the measured capacitance was 2.49, 2.48, 2.65, and 2.49 pf, respectively. The response of a laser machined gap capacitor appears relatively flat up to 4 GHz.

A further study was made of the effect of gap width on capacitance value. Fig. 9 shows the results of a tantalum-chrome-gold composite film on a polished sapphire substrate, and of a chrome and gold composite on an unglazed barium titanate substrate. Calculated points from Fig. 6 are indicated to show the agreement with the analytical model. The data indicates that the gap capacitors are insensitive to changes in gap dimensions when the gap is a few mils wide, but very sensitive when the gap is made less than a mil across. These results suggest that in order to achieve the highest possible specific capacitance it is desirable to achieve the smallest possible gap width. On a normalized plot, such as Fig. 9, the elements are also insensitive to substrate dielectric constant and the dielectric properties of the test environment. Gap capacitance therefore can be presented on a normalized basis with some constant as a dielectric scaling factor.

We show in Fig. 7 that capacitance varies linearly with length for straight-line gaps. To achieve a high capacitance per given area,

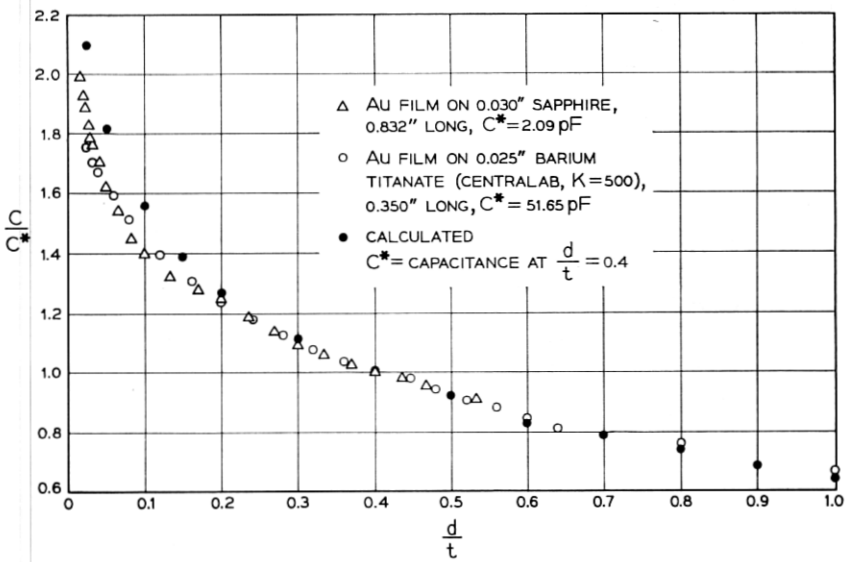


Fig. 9 — Capacitance of gap capacitors as a function of gap width.

however, the gap may be fabricated in a serpentine geometry. Fig. 10 shows a portion of a serpentine capacitor with 0.5 mil gap and 5 mil spacing. Fig. 11 shows the results of capacitance as a function of total line length for serpentine gap capacitors of equal heights on a conductor 0.225 inch wide. The curve is linear down to about a 50 mil spacing between the parallel legs. As this dimension decreases, the relationship between capacitance and line length becomes nonlinear. These results suggest the interaction of fields remote from the gap edges that significantly affects the value of the element.

Specific capacitance is one means of comparing different thin film capacitors. A specific capacitance can be given for gap capacitors provided the substrate dielectric constant and gap width are stated. Laser machined gaps 0.5 mil wide have been made in films on 200 mils-square sapphire substrates ($K \sim 10$) in a serpentine fashion with values up to 18 pf. This corresponds to a specific capacitance of 4.5×10^{-4} pf per square mil. It is estimated that this value can be increased to about 1×10^{-2} pf per square mil by adjusting the serpentine geometry and decreasing the gap width to 0.2 mil. Such gap widths have been machined in thin films with the YAG laser when the optical alignment and beam control have been precise. With careful control of techniques and equipment, repeatable gap widths of a few microns or less are practical.

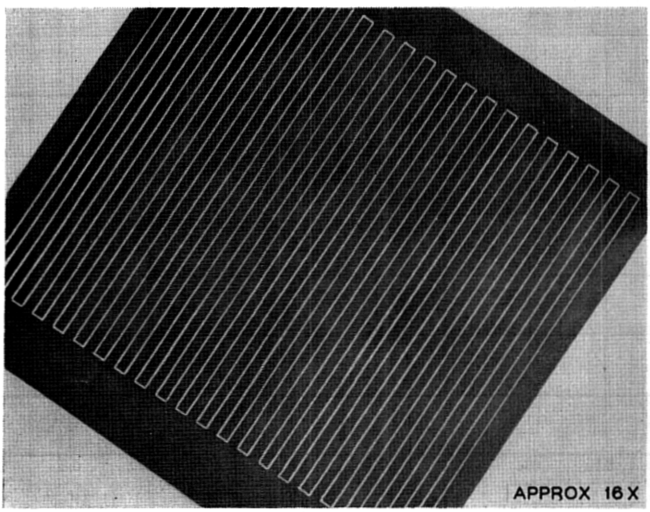


Fig. 10 — Serpentine gap capacitor on sapphire substrate. Gap width 0.5 mil, separation between legs 5.0 mils.

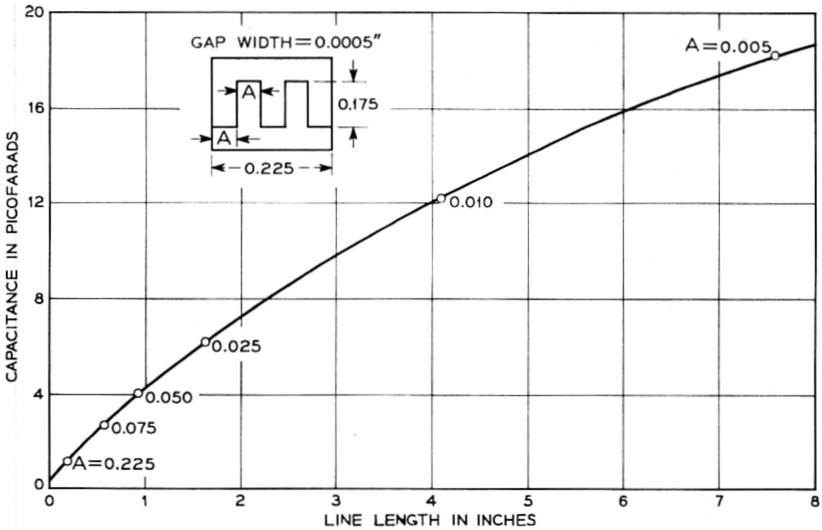


Fig. 11 — Capacitance of serpentine gap capacitors as a function of total length of gap.

Leakage currents less than 10^{-9} amperes at 40 V are normal for these units. These values indicate that there is very little debris remaining in the gap.

3.2 *Trimming Thin Film Resistors*

Two techniques for increasing the resistance of tantalum nitride resistors with the YAG laser have been explored. Initial studies have established the feasibility of trimming to value by removing material and by thermal oxidation.

Trimming by removing material may be accomplished either by changing the dimensions of the resistor or by vaporizing small spots in the interior of the resistor. Fig. 12 shows a resistor whose value has been increased 19 per cent by means of a series of internal spots, each vaporized with a 1/50-second exposure to the Q-switched beam. Included in Fig. 12 are the results of resistance measurements taken on this resistor.

Changes in resistance from less than 0.01 to over 0.1 per cent per spot have been demonstrated by varying the size and location of the spot on the resistor. Fig. 13 demonstrates typical resistance changes for a resistor, one of whose edges has been removed progressively in

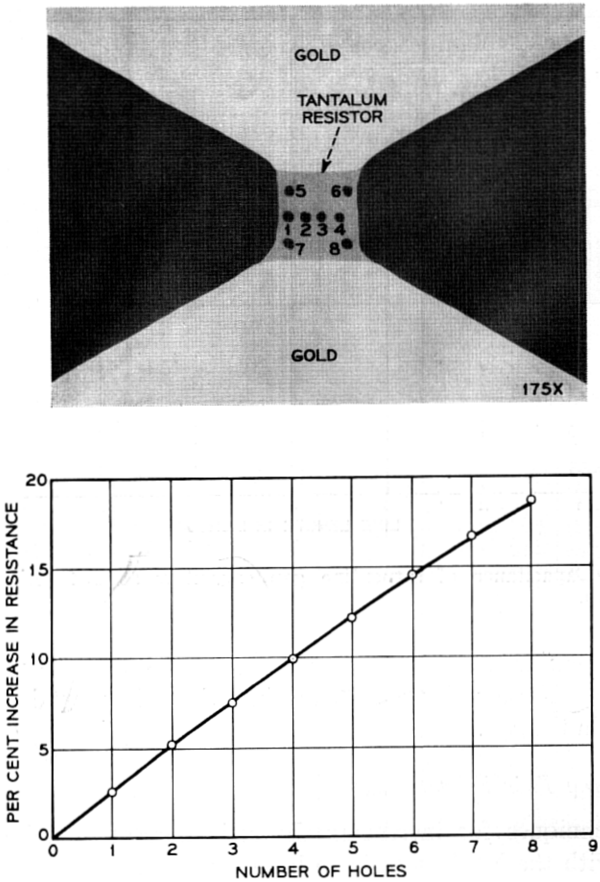
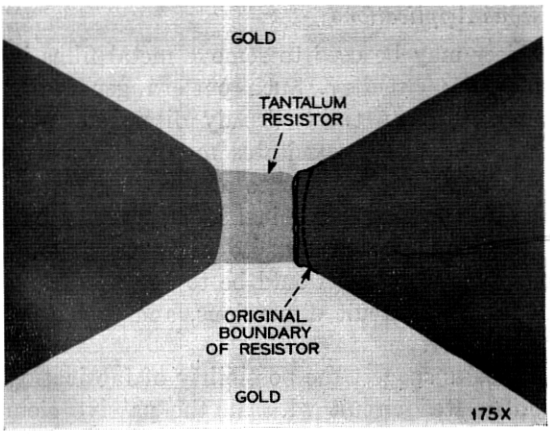


Fig. 12 — Resistor trimming by spot material removal.

0.0001-inch steps. With proper instrumentation and control, either the spot or edge laser vaporization method could provide a rapid means of trimming resistors to better than 0.1 per cent. We notice that resistors trimmed by material removal change less than 0.1 per cent in resistance after such resistors are exposed to the laboratory environment for several months. These results suggest the temporal stability of laser trimmed resistors. A definitive measure of stability, however, will necessitate a power aging test under controlled conditions.

Our studies of thermal oxidation were exploratory because a proper quantitative investigation will require a laser with sufficiently high output to achieve the required power density over a spot large enough to completely expose the entire resistor. In the present study, a spot about 0.001 inch across was used and the resistor surface (0.005 inch square) was swept past the beam. A uniform brown color resulted, accompanied by a change in resistance from 16.96 to 17.98 ohms. The same color and increase in resistance may be obtained by wet anodization to a potential of about 20 V.

A much greater increase in resistance (for example, 16.29 to 38.26 ohms) was obtained by further exposure. The surface, however, ap-



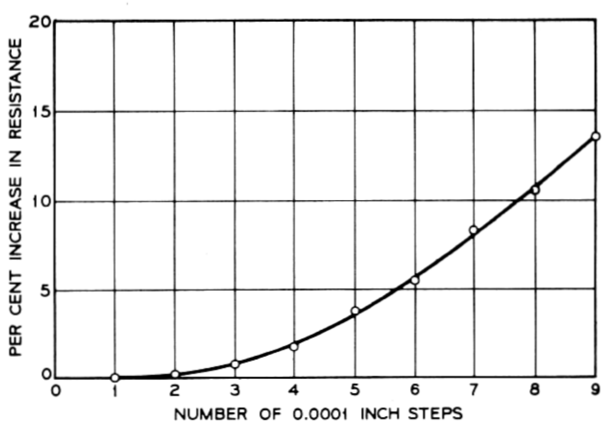


Fig. 13 — Resistor trimming by edge material removal.

pears nonuniform in color, indicating the varying degrees of oxidation. As treatment progressed, the process appeared to lose stability in the sense that it required greater attention to laser output and stage sweep speed to prevent the resistor from burning through locally. The indication is, however, that both uniformity and stability will improve when larger laser spots are used.

We noticed that oxidation of tantalum areas adjacent to gold conductors is possible without damage to the gold. The high reflectivity of the gold raises the damage threshold of gold well above the power required for converting the tantalum to oxide.

3.3 *Miscellaneous Applications*

The YAG laser may be used to remove metal films in order to define interconnecting circuitry. Such pattern generation requires no considerations other than those already discussed. With the present laser the small spot size necessitates many passes by means of an index-and-repeat method, in order to remove large areas of film. Such a method would be more economical if the present YAG laser were Q-switched at great speeds so as to allow correspondingly greater sweep speeds. An alternative would be to use a higher powered laser to define roughly the circuit dimensions, and then to trim precisely with the present laser.

The initial results suggest the possibility of fabricating, in one step, a complete integrated circuit with all the passive elements. Such a process would start with a metallized substrate and would use a programmable laser and work stage. Complete laser fabrication of hybrid circuits will require a process in which a metal film is removed selectively, exposing a different film. For example such a process may be necessary in order to remove the conductor and expose the resistor film.

In the present tantalum-chrome-gold technology such a selective removal of the gold presents substantial difficulties because the reflectivity of the gold is much greater than that of the tantalum nitride. It is quite probable, however, that some combination of films will be found for which the upper film can be removed from the resistor without damaging it.

IV. MACHINING THIN-FILM MASKS

The machining of masks involves considerations similar to those for pattern generation. Experience has indicated that a variety of sputtered and deposited films (1000—3000 Å) on quartz, glass, and sapphire may be machined conveniently. Patterns machined in titanium and nichrome films, however, appear to have superior edge definition and uniformity of transmitted illumination compared with patterns produced in other films. Mechanisms governing the behavior of the metal film during laser machining have not yet been defined, but appear to depend upon the surface tension and bonding characteristics of the film as well as the thermal properties of both film and substrate.

V. SUMMARY

The feasibility of machining resistive and capacitive components directly on thin film metallized substrates with a laser has been demonstrated. Tantalum films can be shaped into resistor geometries and trimmed to tolerance by removing metal. These films also can be oxidized to value using the laser beam as the heat source. Resistors can be made with tolerances in value of less than ± 0.1 per cent.

Gap capacitors have been made on sapphire substrates with capacitance measuring up to 20 pf in an area of 0.04 square inch with 0.5 mil gap spacing. Limited studies have indicated that these elements are stable with time, have leakage currents at 40 V of less than 10^{-9} amperes and do not change significantly with frequency up to 4 GHz. Variation of capacitance with gap width has been studied and experimental results show good agreement with numerical results based on an analytical model for determining parasitic capacitance.

Pattern generation by laser machining has been demonstrated on various thin films as well as on electroplated films. Vaporized lines as fine as 0.25 mil are readily attainable in thin films, as are 0.4 mil lines in plated films. Much narrower lines may be obtained under particularly well-controlled conditions. Uniform lines as fine as 1 micron have been scribed in thin films on sufficiently flat substrates. These films have been removed with minimum effect to the substrate surface.

The present work has been accomplished with a Q-switched YAG laser operating with a repetitive output, at 400 hertz, of 1 kw peak power and 200 ns pulse duration. Advantages of such a laser as a machining tool include the optical quality of the output, and simplicity and economy in both design and operation. Maximum machining speed presently approaches 0.1 inch per second for 0.2 mil gaps, and a further increase of one to two orders of magnitude may be expected as the repetition rate of the laser is increased. Continued development of the YAG laser, particularly with regard to decreasing the width of the pulse, is expected to provide for increased definition of the working zone, improved selectivity in removing films of various metals, and a further decrease in the already small damage to the substrate.

Our study has been exploratory and has served only to establish the feasibility of machining thin film circuits with existing lasers. Further attention to the details of the specific machining processes as well as to the combination of these processes into an automated procedure is necessary in order to evaluate their practicality. It is necessary, also, to better define the mechanisms governing laser material removal processes in order to realize fully the potential applicability of laser machining of thin film circuits.

ACKNOWLEDGMENTS

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Miss E. B. Murphy performed the numerical calculations in Section III on a digital computer. We appreciate the interest of J. W. West, C. Maggs and L. Rongved, all of Bell Laboratories.

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