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Laser surface modification for selective electroplating of metal: a 2.5 m/s laser direct-write process*

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Abstract

A very fast laser direct write process is described. The process involves laser modification of an insulating seed multilayer to form a conducting surface which can be electroplated. The seed layer is composed of an adhesion layer of TiW, a conducting layer of Au, and a top insulating layer of a-Si. The laser forms a Au-Si mixture without substantially affecting the adhesion layer. Writing speeds of 2.5 m/s have been demonstrated. The laser patterning can be performed in air, and the process works over a broad range of laser power ($P_{max}/P_{min} \sim 5$).

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Laser processing continues to be of interest to the semiconductor industry.[1-5] Laser direct write processes are of particular interest in multichip module (MCM) packaging,[6,7] where alignment tolerances of dice to substrate are such that photolithographic techniques cannot be used for patterning chip to board thin film metal interconnects. A major drawback to the commercial viability of most laser etching and deposition processes is their slow speed. Laser seeding processes[8-10] promise to be considerably faster. These processes cleverly leave most of the metal deposition to a conventional process; the laser only serves to activate the surface, usually by depositing a seed layer which catalyses the subsequent deposition process (e.g., chemical vapor deposition). In several of these processes, however, the morphology and electrical conductivity of the final metal film is inferior to the bulk material, or the adhesion of the seed layer to the substrate cannot be controlled to the extent required of thin films in conventional semiconductor metallization.

We have developed a metallization process (Fig. 1) which uses electroplating to create metal lines in regions which have been written with an argon-ion laser. The laser modifies the surface layer, changing it from an insulator to a conductor. The top layer of an insulator material (amorphous silicon) absorbs the photons of the laser beam, heats and alloys[11] the top layer with an underlying conductive layer of gold. The presence of the conducting gold layer allows current to be conducted across the wafer surface so that those areas (and only those areas) addressed by the laser can be electroplated. Electroplating rates are typically 100 times greater than electroless deposition rates, so that the presence of the underlying gold layer is a significant practical advantage of the present process. After plating, the layers are selectively removed with dry and wet etching, leaving the plated lines standing on a dielectric layer.

The substrates used in the experiments reported here were 100 mm p-type <100> Si wafers with 1 μm of thermal oxide on the surface (a further layer of PECVD oxide of varying thicknesses was deposited for some experiments). An adhesive layer of TiW (400 Å) was sputtered onto the oxide surface, followed by sputtering of a gold layer (2000-10000 Å). An a-Si film (500-6000 Å) was deposited by direct sputtering from a silicon target, or by PECVD of silane (both techniques were employed successfully). The a-Si deposition must be performed at low temperatures to prevent Au-Si eutectic formation (mp = 363° C) or extensive interdiffusion of the gold and silicon.

The laser used in the process was a 12 W argon ion laser operating at 514 nm. Incident power on the wafer surface ranged from 100 mW to 2.5 W on an area of 100 to 250 μm^2. The incident power necessary to initiate writing (threshold) varied substantially with the thickness both of the gold (from 2000 Å to 10000 Å) and SiO_2 (from 1 μm to 20 μm) films, but was not very sensitive to the Si film thickness over the range of 500 Å to 4000 Å. An upper limit the maximum power which could be used to laser write was the power at which dewetting of the gold, silicon, and adhesion layers from the surface occurred. Energy dispersive X-ray analysis confirmed the absence of both titanium and tungsten from the dewetted regions, suggesting that the adhesion layer dissolved in the gold-silicon melt at sufficiently high temperatures, causing the seed layer to dewet the underlying oxide surface. The laser process performed successfully both in argon and in air (Fig. 2a shows a series of lines which were laser written in air at 10 mm/s). The process window was large (Fig. 3), and varied with the thickness of the gold layer; the maximum possible laser power for successful alloying was 4-6 times the minimum laser power for a gold thickness of 4000 Å.

Our direct-write system (Fig. 4) incorporates Kennsington 8500 translation stages, an aperture controlled by an Isomet 1200 accousto-optic modulator (AOM), and in-house software. The stages provide x, y, and theta movement; the laser beam position remains fixed. The maximum speed of the stages is 11 cm/s. The exact speed was determined by monitoring the input to the AOM, and measuring the length of the written line. The velocity of the stages determines the dwell time of the laser on any point on the surface. The dwell time, together with the laser power and the thermal conductivity of the various substrate layers, determines the extent of the surface alloying. Stage speeds greater than 11 cm/s, therefore, can be simulated by pulsing the laser beam by means of the AOM in order to reduce the dwell time. A software controlled function generator was used to provide a single pulse of a specified duration every 100 μm at a stage speed of 10 cm/s (this procedure prevented pulse overlap for pulses shorter than 1 ms).

After laser writing, 2-5 μm of copper (Fig. 2b) were typically plated from a $CuSO_4/H_2SO_4$ solution in a flow plating apparatus. Auger depth profiling studies showed that a 30-50 Å layer of SiO_2 can form on part of the surface of the laser written lines for both air and argon samples (the latter SiO_2 layer presumably forms when the sample is exposed to air following laser writing), and this can result in some unplated regions. A dilute HF clean (100-to-1 HF for 10 s) prior to plating clears the oxide and results in uniform plating.

Seed layer removal involves dry etching a-Si in an SF6 plasma (50 mtorr; 150 W; 25 sccm; ~1 min) to expose the gold, which is then wet etched in gold etchant (triiodide solution). In order to prevent the etching of copper during the gold removal step, a Ni layer is plated over the Cu before the a-Si is removed. This procedure can be problematic if the nickel film is porous or has defects, because the gold etchant attacks copper at a much faster rate than gold. Alternate gold layer removal schemes include ion milling and electro-anodic removal. The TiW adhesion layer is removed with the same SF_6 plasma used to etch the a-Si.

The new alloying process wrote easily at speeds of 11 cm/s (the maximum velocity of the stages), with an incident laser power of 1 W. The written lines were as well defined at 11 cm/s as at 1 mm/s. In order to examine the upper limit of the writing speed for our new process, a series of pulse experiments were carried out. Without pulsing, the dwell time of the laser beam on any point of the wafer surface is the beam width divided by the stage speed (e.g., at 10 mm/s, a 5 μm beam dwells on any single point for 500 μs). By pulsing the laser, the dwell time becomes the pulse duration provided that the pulse repetition rate is low enough to prevent a given point from seeing more than a single laser pulse. At 10 mm/s, the stage speed can be ignored for pulses less than 50 μs, because the stage moves only 1.0 μm every 50 μs, so edge effects are minor. Writing on a wafer with 2000 Å a-Si on 4000 Å Au at 2 W of incident laser, the shortest pulse with which we were able to laser write and plate was 2 μs, which corresponds to a laser writing speed of 2.5 m/s. At 2.5 m/s, a 4" wafer (100 mm diameter; 78.5 cm^2) could be patterned completely with 10 μm lines (20 μm pitch) in 160 s.

A 2.5 m/s laser direct write system is not currently practical, but a multiple beam system operating at a slower speed is. But even at 11 cm/s (the maximum speed of our current stages), die to board interconnects can be produced at rates which rival current technologies. The rate at which 1 mm by 10 μm wire connections can be formed is about 50 wires/s (to avoid acceleration and deceleration delays, the stages are rastered parallel to the line edges and lines are written piecewise 25 μm at a time. The beam is 5 μm wide in the direction of the stage travel and 25 μm long in the perpendicular direction). By comparison, wire bonders connect 2 wires/s while laser TAB bonders connect 32 wires/s. At 2.5 m/s (or a multiple beam equivalent speed), the rate of interconnection would be 22 times as fast. At such fast rates, the interconnection process would probably be limited by the setup time, not the laser writing speed.

In conclusion, we have developed a laser direct write process which can attain a single beam equivalent speed estimated at 2.5

m/s, and has a broad process latitude ($P_{max}/P_{min} \sim 5$). With this added speed, laser written thin film interconnects can definitely compete with existing MCM interconnect technologies, with consequent improvements in pinout density and operating speed. The process produces metal lines with good morphology, adhesion, and electrical characteristics, unlike most laser seeding technologies.

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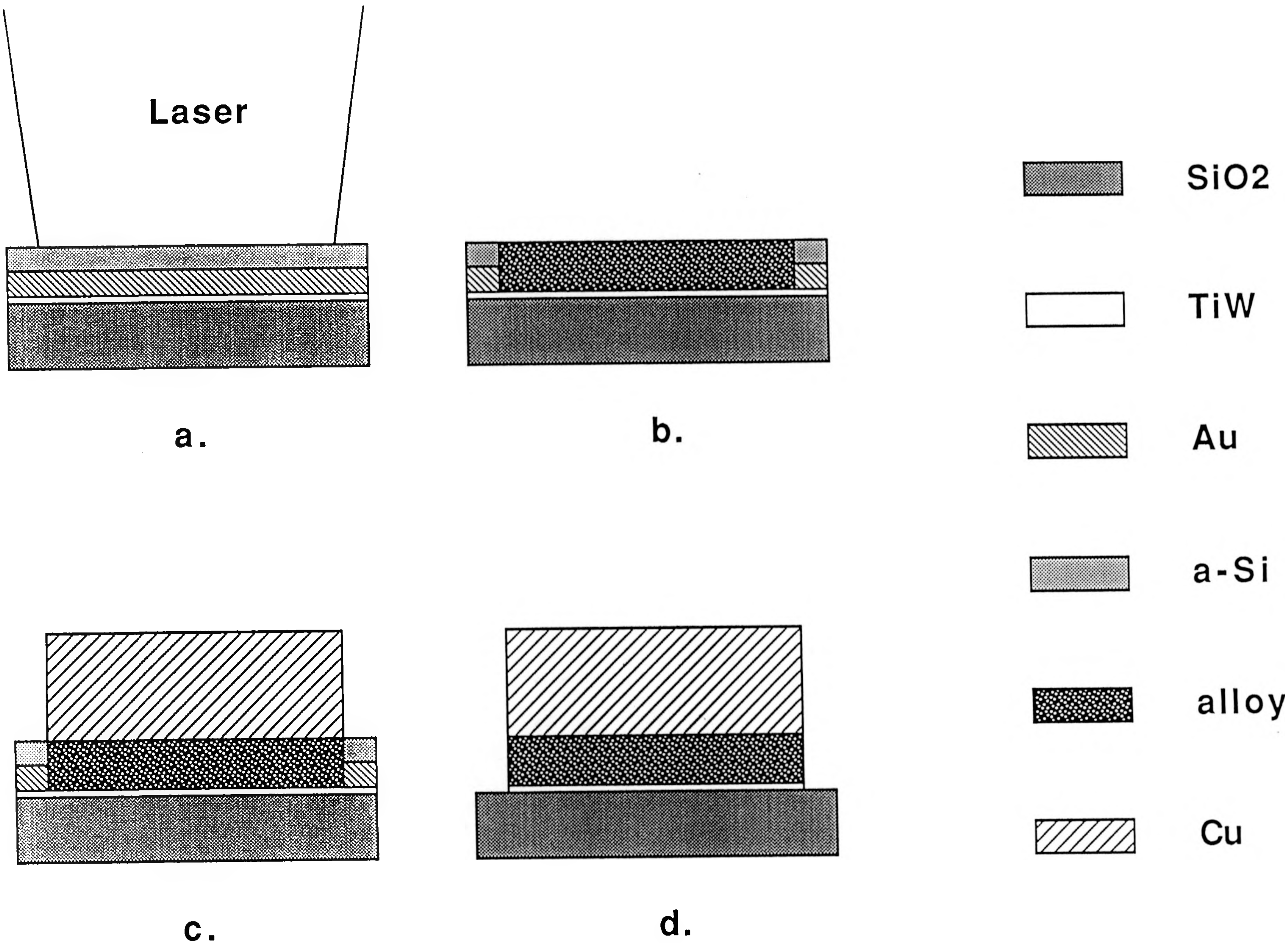
Figure Captions

Figure 1. Process flow: a) a Si wafer with films of SiO_2, TiW, Au and a-Si is written with an argon ion laser; b) a melt has formed and frozen; c) Cu is plated on the laser written alloy; d) the seed multilayer is removed, leaving a conducting line standing on a dielectric surface.

Figure 2. SEM's of 20 µm lines with 40 µm pitch (magnification 400X; inset is 2000X). a) After laser writting, and b) after copper plating. The lines were written in air at 10 mm/s, with 0.5 W incident laser power. The seed layer is composed of TiW(400 Å), Au(6000 Å), and a-Si (2000 Å) on 1 µm thermal oxide.

Figure 3. Process window (P_{max}/P_{min}) for seed layers composed of 4000 Å Au, and several differnet thicknesses of a-Si. The oxide underlayer was 10 µm, and the stage speed was 10 mm/s.

Figure 4. Schematic of laser direct write system.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b.
c.
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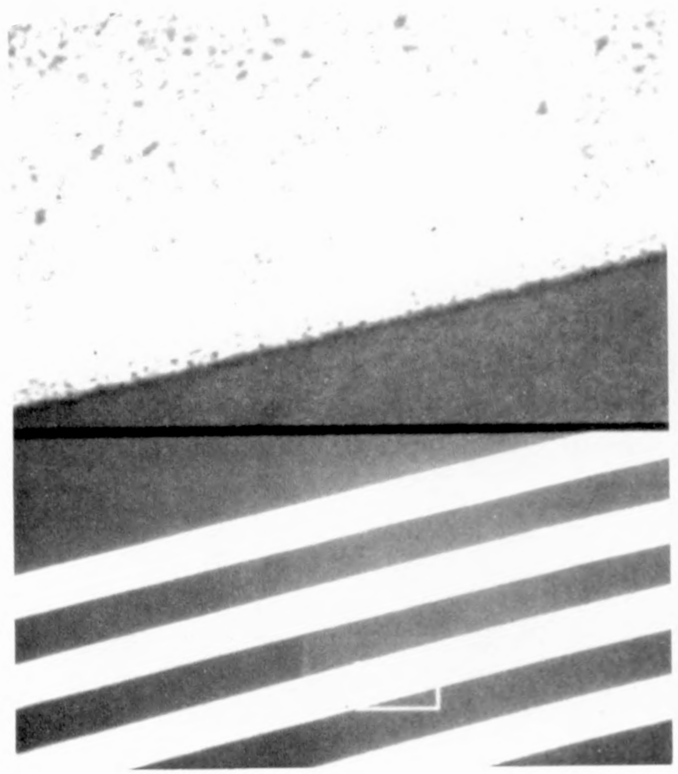
SiO2
TiW
Au
a-Si
alloy
Cu



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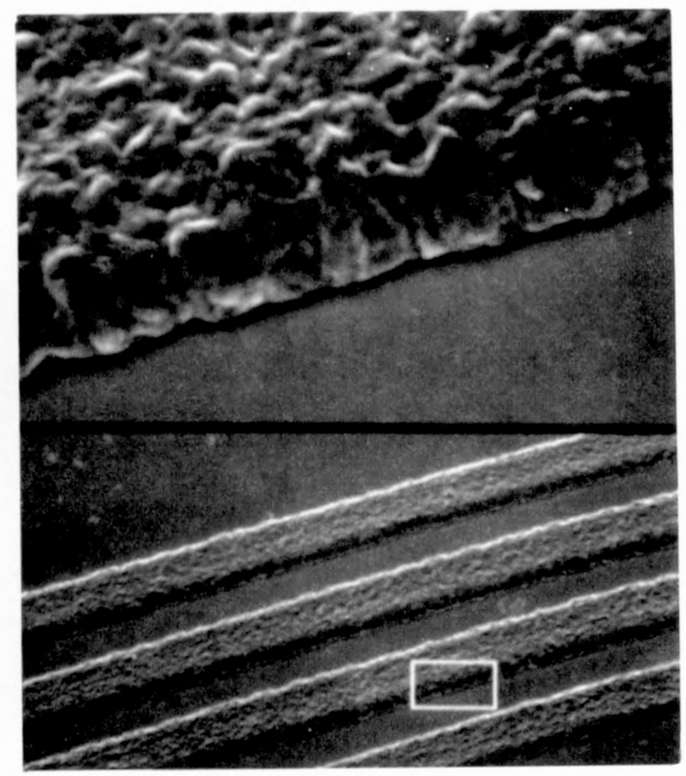

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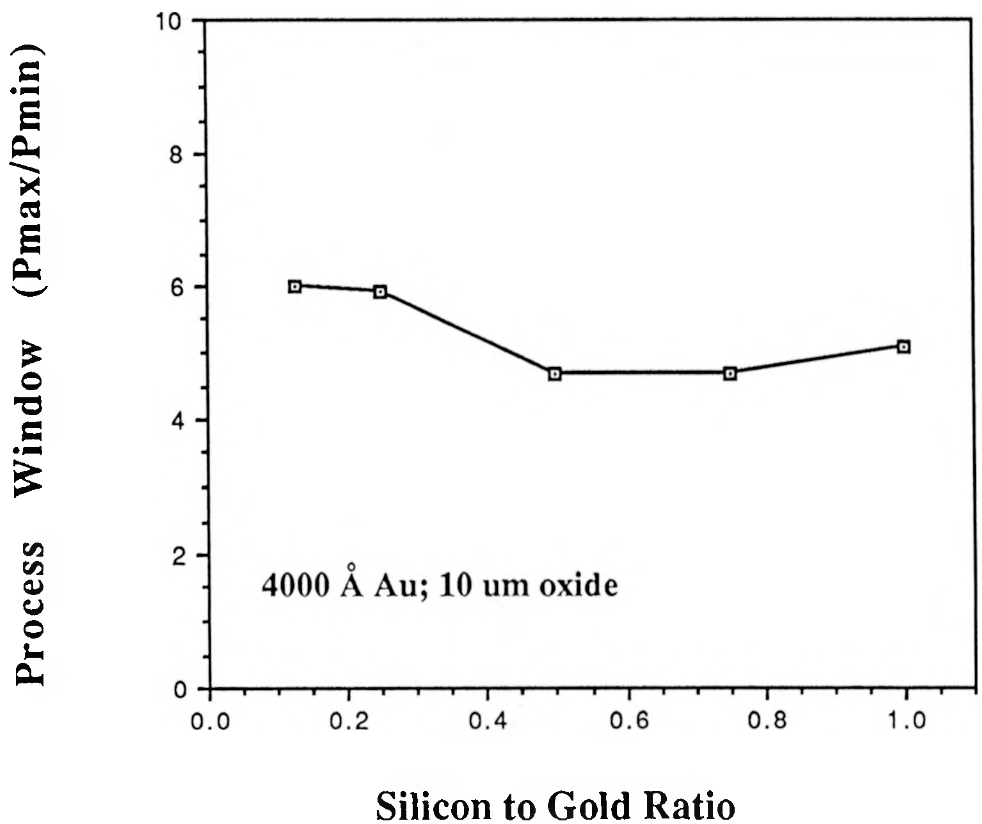
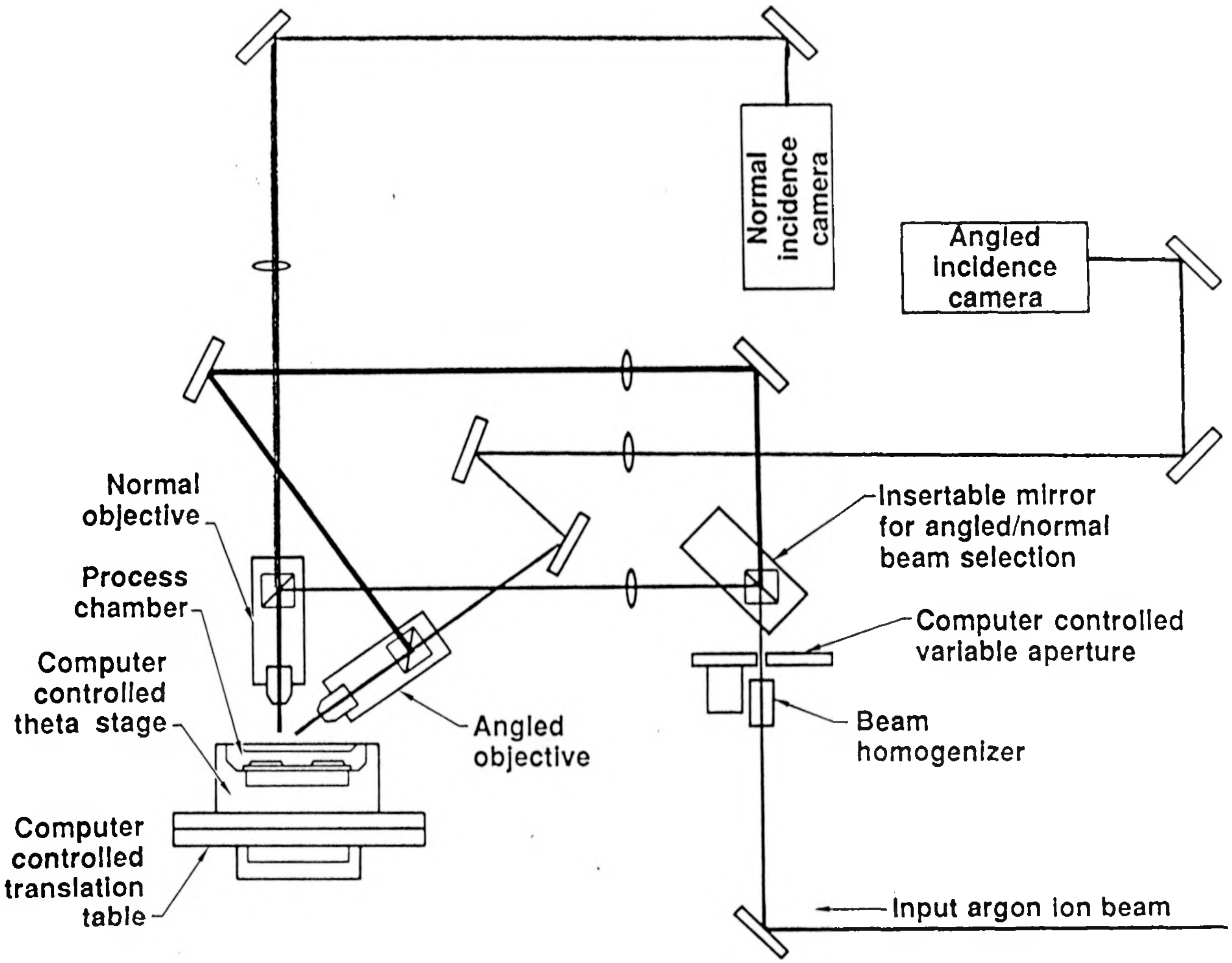

Process Window (Pmax/Pmin)
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
4000 Å Au; 10 um oxide
Silicon to Gold Ratio



Normal incidence camera
Angled incidence camera
Normal objective
Process chamber
Computer controlled theta stage
Computer controlled translation table
Angled objective
Insertable mirror for angled/normal beam selection
Computer controlled variable aperture
Beam homogenizer
Input argon ion beam

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