A Metallization System for UHF and Microwave Power Transistors

ALUMINUM METALLIZATION

The limitations of aluminum metallization were noted in some early integrated circuits where narrow interconnect patterns and high device densities pushed the current densities to an intolerable level. Subsequent studies by J.R. Black (Motorola SRDL) and others defined exactly what the limitations of aluminum are and what might be expected of some other materials as well.

The failure rate over temperature for aluminum at a current density of 3×10^5 A/cm^2 is shown in Figure 1.

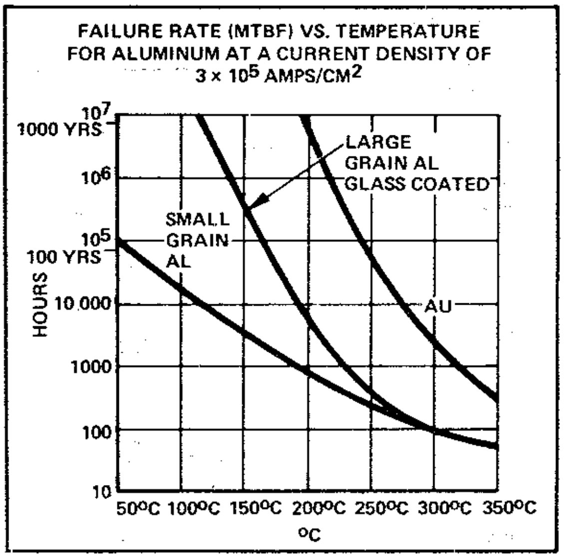
FAILURE RATE (MTBF) VS. TEMPERATURE FOR ALUMINUM AT A CURRENT DENSITY OF 3×10^5 AMPS/CM^2

FIGURE 1

In some early designs it was not uncommon to encounter this density level, and as can be seen from the graph, for fine-grain aluminum, at 200°C the mean time before failure (MTBF) is less than 900 hours! To some, the 200°C level might seem somewhat extreme but conservative design is an absolute necessity for high reliability in the high-frequency power area. Figure 2 gives the MTBF vs current at 200°C for a conductor stripe 12.7μ wide by 1μ thick. Given the desired operating current level it is quite simple to calculate the MTBF.

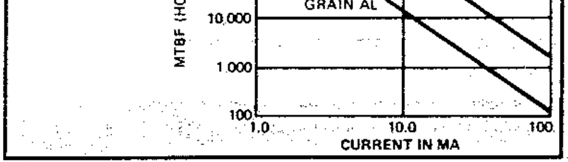

FIGURE 2

It should be noted here that the source of these curves and of most of the MTBF numbers quoted here and elsewhere in the industry are from tests on carefully controlled test vehicles consisting of dog-bone resistor patterns, or, in some cases, from theoretical calculations based on the activation energy of the material involved.

The familiar metal migration or electromigration of the conductor also has some secondary effects. At the point where silicon and aluminum are in contact, silicon is removed and replaced by aluminum. The SEM photo, Figure 3, shows the "etch-pit" formation that results.

FIGURE 3

This phenomenon seems to occur much more rapidly along the silicon/silicon dioxide interfaces. In RF power devices this can ultimately lead to emitter-base shorts if the device is operated at elevated power and/or temperature for extended periods The use of a "barrier' metal or layer between the aluminum and silicon has proved to be a workable solution.

STEP COVERAGE OF 1.2 MICRONS OF Al OVER 0.75 MICRON TAPERED OXIDE STEP

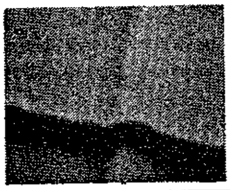

FIGURE 4

Another potential reliability problem that is more related to deposition methods than to the materials is step coverage of aluminum films over the SiO_2 Figure 4 shows the ideal case but in fact the extremes range from the ideally tapered (A), to the sharply under-cut (B) shown in Figure 5.

SCHEMATIC DIAGRAM OF TWO TYPES OF STEPS THAT OCCUR IN DEVICE FABRICATION

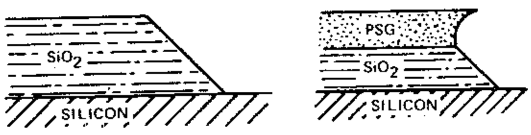

FIGURE 5

With the sharply under-cut condition a microcrack in the metallization can form This microcrack is represented in Figure 6. The microcrack is nearly impossible to detect with a normal microscope.

SCHEMATIC CROSS SECTION SHOWING MICROCRACK IN DEPOSITED METAL FILM

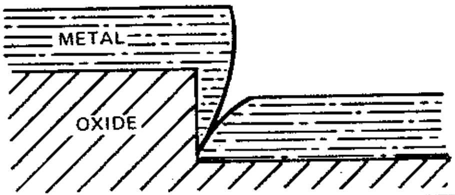

FIGURE 6

OTHER METALLIZATION SYSTEMS

A replacement for the aluminum contact system we have used successfully for a long time, a system which is outmoded *only* on "state-of-the-art" semiconductor devices, must be approached with great care. The change of contact metals may well approach in significance and difficulty the switch from silicon mesa to the silicon planar technology It is important that the change be carried out in a disciplined and ordered fashion. Dick Wilson, Lou Terry, and others at Motorola have considered a variety of metal systems and tested them for performance. Considerations for any new metallization system are shown in Table I.

A	The material should have a high conductivity ($\rho < 10\mu$ ohm-cm)
B	It should have good adhesion to both the semiconductor material and to thermally grown or deposited dielectric films
C	The metal or metals should be free from degrading intermetallic compounds not only between metal films but between the metal and the semiconductor
D	Should make a good low ohmic contact to both P- and N-type silicon
E	Amenable to practical production methods of deposition and delineation
F	Resistant to current induced electromigration
G	Resistant to electrochemical corrosion.
H	The deposition of the metal or metals must not introduce surface instabilities in the semiconductor material
I.	The metallization system must be compatible with LSI arrays involving multilayer interconnection processing

TABLE I

Only the first four or five materials in Table II can be seriously considered for UHF and microwave power devices due to the necessity of keeping resistive losses as low as possible for a given pattern configuration. Silver can be eliminated due to the tendency to oxidize in normal environments Copper can be eliminated for similar reasons. We don't know much about beryllium from a processability standpoint, except for the toxicity of its oxides. At any rate, this material is a little high in resistivity. Discounting Al, since it is the one we wish to replace, we are left with gold.

Metal	Volume Resistivity in Micro-ohm Centimeters	Ohms Per/Square for 6000 A – Thick Film	Resistance of A 10-Mil-Long Conductor 2-Microns Wide X 6000 A Thick
Ag	1 61	2 7 X 10^{-2}	3 4 (ohms)
Al	2 74	4 6 X 10^{-2}	5 8 (ohms)
Au	2 44	4 1	5.2
Cu	1 70	2 8	3 5
Be	3 25	5 42	6 9
Ir	5 3	8 3	11 1
Mg	4 3	7 2	9 1
Mo	5 3	8 8	11 1
Ni	7.8	13 0	16 5
Pd	10 8	18 0	22 5
Pt	9 8	16 4	10 5
Rh	4 7	7 8	9 9
W	5.3	8 8	11 2

TABLE II

ELECTROCHEMICAL CORROSION TEST RESULTS			
METAL	TYPE OF FAILURE	TIME	REMARKS
AL	ALL CONTACTS OPEN	5 MIN	(-) TERMINAL SOMEWHAT FASTER
TI-PT-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
TI-PT	SLIGHT RESISTANCE CHANGE	24 HRS	AU WIRE BOND OPENED
TI-RH	SLIGHT RESISTANCE CHANGE	24 HRS	AU WIRE BOND OPENED
CR-AG-AU	OPEN (CR)	5 MIN	CR FROM UNDER AG-AU. EVEN WITH GLASS OR Si_3N_4 OVERCOAT
TI-AG	LARGE RESISTANCE INCREASE	5 MIN	AG CORRODES BUT NOT REMOVED
HF-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
TI-AG-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATING (+)
TI-MO-AU	OPEN (MO)	5 MIN	MO FROM BETWEEN TI & AU
TI-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
MO-AU	OPEN (MO)	5 MIN	MO FROM UNDER AU. EVEN WITH GLASS OVERCOAT
CR-AU	OPEN (CR)	5 MIN	CR FROM UNDER AU
W-AU	RESISTANCE INCREASE	2-3 HRS	W REMOVED SAME RATE AS AU
ZR-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
NB-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
TA-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
NI-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
CO-AU	RESISTANCE INCREASE	3 HRS	AU DEPLATES (+)
V-AU	OPEN (V)	5 MIN	V REMOVED (+) FROM UNDER AU

TABLE III

The test which was used to generate the data shown in Table III was performed in a 95°C, 95% relative humidity environment. The test structure consisted of two parallel dogbones on SiO_2 coated silicon, the first biased positively relative to the second. The results are of course relative. We will note three of the materials listed Aluminum performed unacceptably on this test. Both Ti-Pt-Au (the Bell Process) and W-Au performed satisfactorily. The only difficulty with the Bell Process is the inability to define the very tight lines and spaces of some microwave and UHF transistor designs.

Metal Silicon Contact Resistance in Ohms, Area 10^{-4} cm^{-2}						
Resistivity (ohm-cm) and Type	Metals					Metal + PtSi
	Al	Mo	Ni	Cr	Ti	
0.001 N	0.09	0.08	0.02	0.03	0.01	0.02
0.01 N	6 (R)	5 (R)	2	3 (R)	4	0.2
0.1 N						45 (R)
0.002 P	0.03	0.06	0.02	0.04	0.01	0.02
0.04 P	1	3 (R)	4 (R)	8 (R)		1.0
0.08 P			45 (R)			3
0.5 P	20	80 (R)	100 (R)	200 (R)		15

(R) Indicates rectifying contact identified by the relation

TABLE IV

Contact resistances of various material to the range of resistivities of both N- and P-type silicon are shown in Table IV. Note that gold is missing–it alloys with silicon at unacceptably low temperatures and cannot be considered as the contact material. The significant fact is that Pt-Si in conjunction with any metal is as good as or better than any material on the chart, with the exception of two points on Ti. Pt-Si has an additional advantage in that the formation of the silicide can be checked visually prior to proceeding with further processing

Looking again at the MTBF due to electromigration induced failures as shown in Figure 1, it should be noted that with gold no significant problem exists until much higher current densities than those now imposed are encountered.

At 3 X 10^5 A/cm^2, and 200°C the MTBF due to electromigration of gold is 1000 years, while under the same conditions—using fine-grain aluminum the MTBF is ≈ 800 hours.

Wilson and Terry using the knowledge of materials gained in these and other tests, developed a structure consisting of platinum silicide used to make contact to the silicon, titanium for adhesion to SiO_2 and Si, tungsten to act as a barrier against gold alloying with the silicon, and gold to act as the main conductor material. The gold pattern was to be defined by sputter-etching using molybdenum as a sacrifical mask

After careful consideration, RF-diode sputtering rather than DC was chosen as the deposition technique to be used in a production process. See Table V.

ADVANTAGES	DISADVANTAGES
1. Simple Two Element Construction	1 High Voltage And Consequently Energic Particles, Produces Substrate Damage
2. Available From Many Manufacturers	2 Large Targets Needed For Large Capacity
3. Easy To Introduce Substrate Bias And Heating	3. Difficulty In Bonding Large Targets
4. Optimum Conditions For Good Step Coverage – (Source-High Gas Pressure)	4 Considerable Substrate Heating From Bombardment
5. RF Systems Deposit From Insulating As Well As Conducting Target Materials	5. Film Properties May Be Affected By Gas Occlusion

TABLE V

Figure 7 shows the Ti, W, Au structure covering what can only be described as a worst case step condition. If there is a micro-crack there, it is not apparent in this view

SEM MICROGRAPH OF STEP COVERAGE OF Ti-W-Au SPUTTERED FILM OVER UNDERCUT POLYSILICON STEP

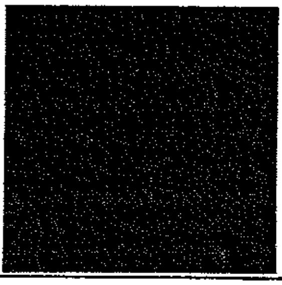

FIGURE 7

The procurement of a production-worthy sputtering system for implementation of this metallization required a large amount of study.

The Pt-Si machine incorporates a heated anode for in situ formation of the silicide. The system is automatically tuned, has auto pressure control, and has provisions for sputter etch and bias sputter. The pallets are loaded in the machine by use of the "intervac" pallet injection system

The 4-target turret head machine is used to deposit Ti, W, Au, Mo in sequence. This system uses a water-cooled anode, auto tune, auto pressure, and the intervac pallet injection system. The machine also has provisions for sputter etch and bias sputter.

The sputter etch machine is used to define the gold contact pattern. Auto tuning is incorporated along with automatic vacuum system control.

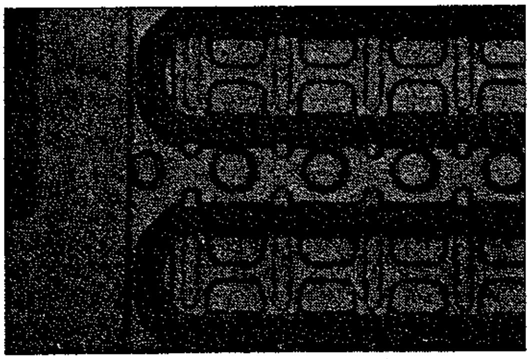

FIGURE 8

Results achieved with this system are shown in Figures 8 and 9, representing a low-voltage, 35-W, 470-MHz power transistor normally utilized in land-based mobile communications applications.

The process demonstrated is now ready for full production utilization. Life testing on devices fabricated in this system have produced zero failures (1,000 000 current cycles/device)

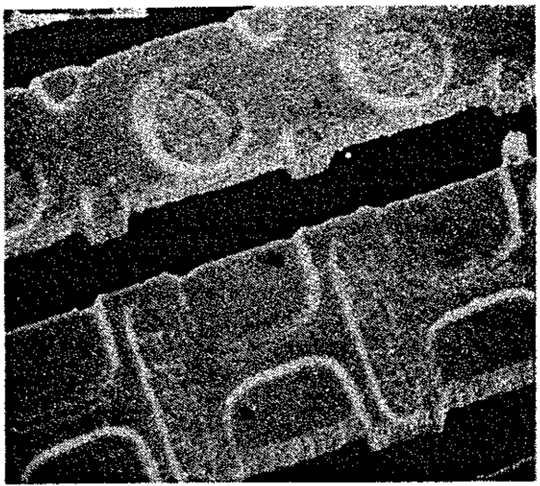

FIGURE 9

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