V_F Forward drop of a junction.
V_S A combination of voltages during the "on" period.
i Current through timing capacitor.
i_3 Current in R_3 during τ_r.
i_{c1} Collector current of Q_1 during τ_r.
I_0, I_{C1} Combinations of reverse currents.
I_{10}, I_{20} Reverse currents of D_1; D_2.
I_3 Current in R_3 at the end of τ_d.
I_{C10} Reverse collector-emitter current of Q_1.
I_{C20}, I_{E20} Reverse collector-base and emitter-base currents of Q_2.
I_{E2} "on" current of Q_2.
$I_{E'2}$ Current of Q_2 when regeneration starts.
I_{G0} Reverse diode current of the trigger gate.
b (normalized base time constant)$^{-1}$.
G $1/R$ throughout.
k Boltzmann's constant.
q | electron charge |.
Q_B Base charge.
t Time.
T Absolute temperature, °K.
T_{BV} Base time constant for varying collector voltage.
T_{CV} Collector time constant for varying collector voltage.
T_r Circuit time constant during τ_r.
x Normalized regeneration time.
Z_{b2} Small-signal input impedance of Q_2.
α d-c common-base current-gain.
$\beta_{2\,on}$ d-c common-emitter current-gain when Q_2 carries its maximum current.
β_{reg} d-c common-emitter current-gain when regeneration starts.
ξ, η Auxiliary parameters.
μ_{12}, μ_{21} Current transfer between transistors.
ψ Relative change per degree of carrier densities in intrinsic semiconductors, and of reverse currents.
τ Total timing period.
τ_d Delay time.
τ_r Regeneration time.

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Gold Alloying to Germanium, Silicon and Aluminum-Silicon Eutectic Surfaces†

L. BERNSTEIN*

Part 2

Alloying To Al-Si Eutectic Surfaces

Early investigators[19] encountered much difficulty in producing bonds to Al-Si surfaces. As previously mentioned, gold alloying repeatedly produced a deleterious purple phase.

When a major development became handicapped by this malfunction to the degree that it was dubbed the "purple plague," a serious program of investigation was instituted.

Reference to the literature disclosed that Zintl[20] had remarked upon the high heat of formation and "remarkable color" of $AuAl_2$. A year later, Coffinberry[21] reported formation of a brittle purple phase which he identified as $AuAl_2$. His measurements showed it to have a calcium fluoride type structure with a = 5.9868Å. Both had been anticipated by West[22] who, in 1934, reported the distance between the gold and the aluminum atoms to be 2.58Å, appreciable less than the sum of the atomic radii (2.87Å).

With a clearer picture of the possible identity of the "purple plague" at hand, a series of synthesis was set up. Wire or preforms of pure gold, pure gold with added dopants, Au-Si, Au-Ge, and Au-Sn were alloyed onto Al-Si eutectic at temperatures in excess of 400°C. In every case, metallographic sections disclosed the presence of the "purple plague", as well as a second "goldish" phase, along with the original Au and Al-Si phases. X-ray diffraction and spectrographic analysis identified the new phases as $AuAl_2$ and Au_2Al, respectively.

For a better look at these compounds, and to isolate them from other constituents, they were prepared from the elements.

Stoichiometric proportions of pure gold and aluminum (99.999% or better) to make $AuAl_2$ and Au_2Al were mixed, placed in quartz capsules which were evacuated, sealed and then heated. At temperatures below the melting point of aluminum (660°C), heating for period up to 48 hours produced no visible re-

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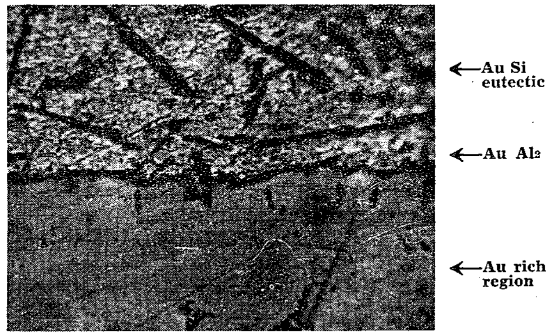

Fig. 9—Al-Si bond to Au at 425°C for 1 minute. (From a 900 X photomicrograph)

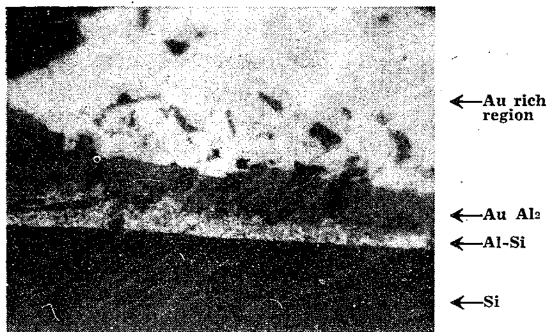

Fig. 10—Al-Si bond to Au at 450°C for 1 hour. (From a 900 X photomicrograph)

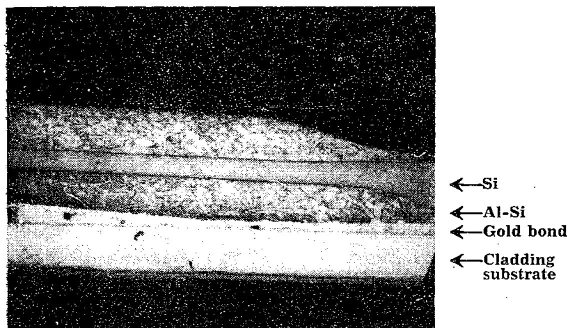

Fig. 11—Typical bond formed at 500°C for 1 minute. (From a 50 X photomicrograph)

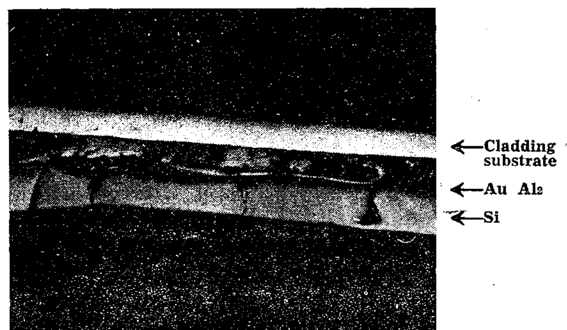

Fig. 12—Fractured bond formed at 525°C for 1 minute. (From a 40 X photomicrograph)

action. Both evacuated and oxide free capsules were then heated to 1100°C for 24 hours, slow-cooled and the samples removed for future measurements. The high aluminum mixture was predominantly purple, and the other "goldish."

It is seen that elevated temperatures are required to produce the gold-aluminum alloys from the elements. Examination of the gold-aluminum phase diagram[23] indicates no possible $AuAl_2$ formation below 625°C. A liquid phase which would permit mixing of Au and Al for compound formation during electrode attachments between Au and Al-Si eutectic would not be expected at any temperature below the eutectic melting point at 577°C. It was, therefore, interesting to find the "purple plague" was actually produced at temperatures as low as 425°C. No bond was successfully formed below 425°C. This was true so long as Au, Al and Si only were present. Fig. 9 shows the formation of the thin $AuAl_2$ film at this low temperature. At temperatures of up to 500°C for *one minute* there was no appreciable increase in the amount of $AuAl_2$ formation.

Allowing the units to soak at 425-450°C for one hour, however, increased the amount of purple phase formation (Fig. 10) tremendously. At 525°C its formation is excessive and practically spontaneous. A typical bond formed at 500°C is shown in Fig. 11. At elevated temperatures or longer soaking times at lower temperatures, bonds formed typically appear as shown in Fig. 12. The interface is porous and non-continuous with resultant cracking of the silicon.

The mechanism for these reactions is believed to be as follows: In the three component Au-Al-Si system there can exist a liquid phase above 370°C (Au-Si eutectic temperature). This liquid containing gold and silicon can dissolve aluminum, thereby raising its melting point and freezing, or form a still lower melting ternary eutectic. In either case, if we consider non-equilibrium conditions, both gold-aluminum compounds can form. Evidence of the solubility of Si in $AuAl_2$ has been found by X-ray diffraction and spectrographic analysis. In addition Si dispersed both in the purple and the goldish phases in the course of electrode attachment has been detected in a metallographic section. This silicon in contact with more gold at temperatures above 370°C produces more liquid, thereby continuing the cycle until equilibrium is reached or the reaction arrested by lowering the temperature.

Generally speaking, the presence of the purple $AuAl_2$ as a *thin film* impairs neither the mechanical strength nor the electrical properties of semiconductor devices when operated at room temperatures and low current levels. There is reason to believe, however, that some devices operating at high temperatures and/or current levels may be adversely affected electrically by the presence of even a thin film. The sensitivity of the metallurgical reactions to time, the co-existence of the two gold-aluminum compounds, and the presence of the five phases in this three com-

ponent system all point out the non-equilibrium conditions under which this attachment is normally made.

Although $AuAl_2$ appears quite dense in ingot form, its behavior in electrode attachment is shown in Fig. 12. Another example showing its typical "eruptive" nature of attachment can be seen in Fig. 13 for small area contact.

Seeking a basis for this behavior, thermal expansion curves (Fig. 14) were determined for $AuAl_2$, Au_2Al, Si and the following eutectics: Au-Sn, Au-Ge, Au-Si, and Al-Si.

Among these thermal expansion curves, that for $AuAl_2$ is noteworthy because of the violent increase in expansion rate above 300°C.

The "hooks" in the expansion curves for gold-tin and Au-Al are possibly due to allotropic transformation, crystallographic rearrangement or just plain non-homogeneous alloying. In the case of the gold-tin however, numerous measurements have shown a departure from linearity in the curve between 150 and 250°C. It is believed that this condition causes serious cracking problems when alloying directly to Si, although not to Al-Si eutectic.

Because of the great differences between the expansion properties of Al-Si and Si, junctions formed by alloy fusion sometimes produce cracking of the silicon. By carefully controlling the junction geometries, thickness ratios of materials and cooling cycle, the danger of cracking or bowing, for that matter, can be completely eliminated. None of the units used in this study showed any evidence of cracking in junction formation.

Of all the alloys studied, the Au-Sn alloyed to the Al-Si most easily. No agitation and/or flux was required and, in addition, atmospheric conditions were least critical. Sound bonds were made even in non-reducing (although inert) atmospheres with dew points as high as +30°F. The Au, Au-Ge, and Au-Si alloying conditions required reducing atmospheres, lower dew points, and in general some weight to overcome surface tension and insure wetting during bonding. Table I shows alloying conditions inherent in producing good bonds.

TABLE 1

Alloying Conditions for Producing Good Bonds

Alloy	% Au	M.P. °C.	Temp. Range in °C Excess $AuAl_2$ Formation	Temp. Range in °C Good Alloy Bonding
Pure Au	100	1063	525-550	425-500
Au-Si	94	370	525-550	400-500
Au-Ge	88	356	425-450	400-425
Au-Sn	80	280	410-425	300-400

In the quaternary systems, with either Sn or Ge present in addition to the Au, Al and Si, evidently enough liquid phase is present to produce substantial amounts of $AuAl_2$ at approximately 100°C lower than in the ternary system.

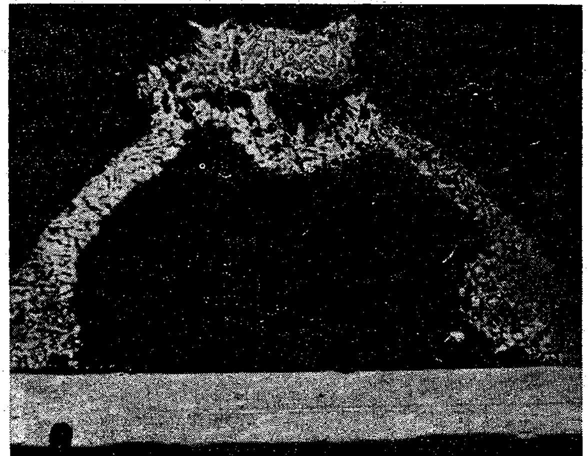

Fig. 13—Typical eruptive nature of attachment with $AuAl_2$ formation in small area contact. (From a 100 X photomicrograph)

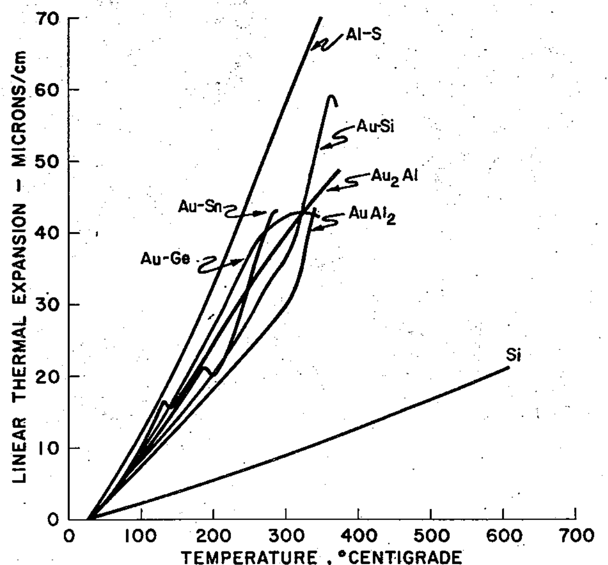

Fig. 14—Thermal Expansion Curves.

In order to fabricate semiconductor devices, one must also provide an electrode attachment to the alloyed surface. If this is done as a two-step process by first melting the chosen gold eutectic on the Al-Si surface, and then inserting a suitable wire material into the molten pool, no problem is usually encountered. If this is attempted as a one step operation, the addition of a suitable electrode wire complicates the wetting problems encountered. The problem was explored further for the Au-Sn system.

At temperatures greater than 280°C a liquid phase is sandwiched between two solid phases. Without the wire material, the Au-Sn wets the Al-Si well. When the sandwich condition exists, the surface energy relationships are such as to direct wetting toward the Au-Sn wire interface and away from the Au-Sn,

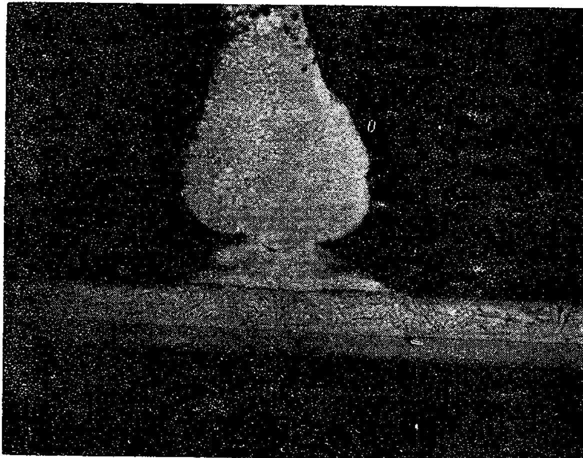

Fig. 15—"Hour-glass" attachment of Au-Sn plus 1% In to Al-Si surface. (From a 50 X photomicrograph)

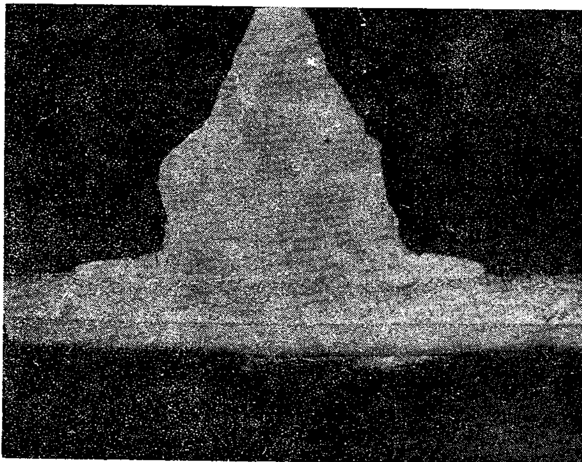

Fig. 16—"Full Wetting" attachment of Au-Sn plus 2% In to Al-Si surface. (From a 50 X photomicrograph)

Al-Si interface for this particular geometry, all other things being equal. The attachment was solely that of Au-Sn to the wire.

From the earlier investigation, it was found that additions of small percentages of indium (up to 2%) improved wetting properties. Preforms of Au-Sn-In were made and assembled with suitable wire material. After proper jigging, satisfactory attachments were made. From the hour-glass shape of the attachment, as seen in Fig. 15 (approximately 1% In), it is apparent that a difference still exists in wettability of the Au-Sn for the wire and for the Al-Si eutectic. The addition of indium was probably just sufficient to improve the wetting of the eutectic to the degree required to make a satisfactory bond.

Figure 16 shows the improvement of wetting to the Al-Si surface by the addition of 2% indium to the Au-Sn eutectic. It is expected that similar results might be anticipated for the Au-Ge and Au-Si systems.

In the aforegoing studies Wittry[24] confirmed the identity of phases formed in these attachments by means of the electron probe X-ray microanalyzer. As expected, the purple phases were shown to be $Au\text{-}Al_2$ and the goldish ones Au_2Al.

Summary

1. Molybdenum tabs should be used where possible because of its excellent expansion match *and* high electrical and thermal conductivities.
   The iron-nickel alloys may be used as tab material where thermal and electrical conductivity are unimportant but magnetic properties are necessary.
   Nickel is not recommended as a tab material because of its poor expansion match to silicon or germanium.
2. Crack-free bonds can be made to the following types of coatings on the aforementioned tabs:
   A. Gold or gold-alloy clad or plated.
   B. Tin* or antimony coated on top of the gold tabs.
   The tin and antimony parts are less sensitive to furnace ambient than the straight gold or gold alloy coatings, which require pure, dry, reducing atmospheres. Pure dry hydrogen is recommended as the best universal gas atmosphere.
3. Additions of 5 wt% indium to gold improve the wetting properties to silicon and germanium.
4. 80 Au-20 Sn readily wets and alloys to silicon and germanium under non-critical ambient conditions, but produces cracking.
5. Additions of up to 6% silicon to the gold-tin eutectic decrease its solubility for silicon and germanium without seriously impairing its wetting properties and reduces cracking.
6. Additions of up to 2% indium to the gold-tin eutectic improve its wettability of silicon and germanium and reduces cracking. Greater additions decrease its wettability.
7. A strong mechanical and metallurgical bond can be made directly to Al-Si surfaces without flux and/or agitation by means of the Au-Sn eutectic.
8. Indium additions to the gold-tin, up to 2 wt%, improve its wetting properties on Al-Si.
9. Two gold-aluminum compounds may be formed in electrode attachments: $AuAl_2$ and Au_2Al. $AuAl_2$ has been referred to as the "purple plague" because of its appearance. Its thermal expansion increases rapidly above 300°C. Its formation has been noted in the presence of silicon at temperatures as low as 425°C and in the presence of both silicon and tin at temperatures as low as 375°C.

*If tin coated tabs are used, precaution must be taken to see that less than stoichiometric tin is deposited. This allows an excess ductile gold layer remaining on the tab. Although this technique eliminated the cracking in silicon attachments, the problem still exists in germanium attachments. It is felt that the greater solubility of germanium in Au Sn is in some way connected with this problem; perhaps thinner Sn deposits will overcome this problem.

Acknowledgment

The author is indebted to William B. Warren (now deceased) and B. G. Bender of Hughes Semiconductor Products for criticism and discussion of some of the experimental results while conducting this work.

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APPLICATIONS ENGINEERING DIGESTS

APPLICATIONS ENGINEERING DIGEST NO. 68

Circle 198 on Reader Service Card

A 175 Mc Distributed Amplifier Using Silicon Mesa Transistors; Fairchild Semiconductor Corp., Mountain View, Cal. (P. J. Beneteau & L. Blaser)

Transistors can be used quite effectively as wideband distributed amplifiers. However, a serious problem presents itself with the later types of silicon mesa transistors in that the usual hybrid—pi equivalent circuit does not appear to be valid throughout a wide frequency range thus making difficult the proper design of the lines. A very simple scheme can be used, however, which yields good results with the 2N706, a transistor with an alpha-cutoff frequency in excess of 500 *mc*. The scheme consists of compensating the 6 *db* per octave drop in current gain by a 6 *db* per octave increase in base current. Four stages of the amplifier shown in Fig. 68.1 gave a voltage gain of about 20 *db* up to approximately 175 *mc*. The impedance level of both the input and output lines is 50 ohms.

Description of the Amplifier

The amplifier stage shown in *Fig. 68.1* contains four transistors arranged in conventional manner, with a base delay line and a collector delay line. These lines have identical characteristic impedances and delays. To maximize the gain, β_o (CE low frequency gain) and R_L should be maximized and R minimized. R_L is determined by circuit convenience (i.e. cabling size) and R is determined by the value of C and the proper corner frequency (see *Fig. 68.2*). The operating point is selected to maximize current gain. Where multiple stages are cascaded, the gain becomes

$$\left[\frac{n\beta_o}{2}\left(\frac{R_L}{R}\right)\right]^N$$

where N is the number of stages; n is number of transistors per stage.

As a pulse amplifier, it is capable of

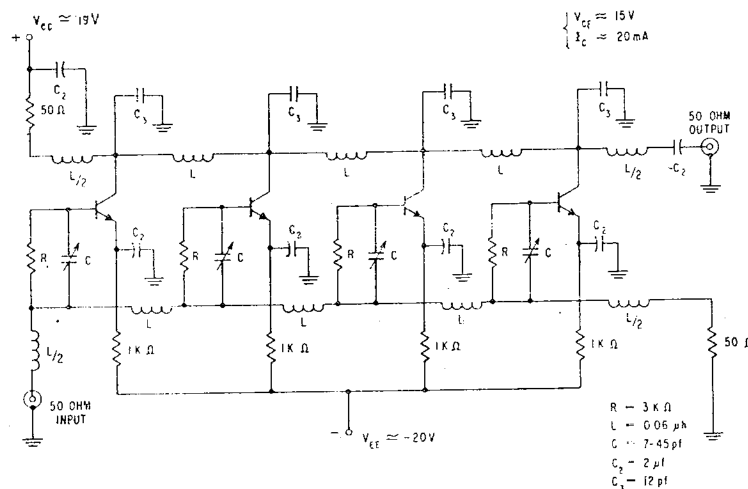

Fig. 68.1—Four-stage wideband distributed amplifier.