TRANSISTOR PRODUCTS, INC.

Gold Bonded Transistor Development

Final Report, 8 Jan. 1954

Contract AF 19(604)-814
Air Force Cambridge Research Center

TRANSISTOR PRODUCTS, INCORPORATED
Snow and Union Streets
Boston 35, Mass.

GOLD BONDED TRANSISTOR

DEVELOPMENT

8 January 1954

FINAL REPORT

R. A. Langevin
Project Manager

Prepared for Contract AF 19 (604) - 814
sponsored by the Air Force Cambridge Research
Center

ADMINISTRATION AND PERSONNEL

Personnel: The present contract began under the direction of Dr. C. G. Smith who had joined the company as project manager of the gold bonded transistor development program. Dr. Smith left the employ of the company in mid July and upon his departure Mr. R. A. Langevin was assigned as project manager and has continued in that capacity to the present time.

The assignment of senior personnel to the project has been in the areas and for the periods indicated below:

Dr. P. R. Richards, Face to face transistors
(July - December)

Dr. G. Knight, Theoretical studies and humidity studies
(July - December)

Dr. R. Johnson - Gold bonding studies
(July - September)

Mr. E. Gschwind, Mechanical design
(July - December)

Mr. D. Humez - One sided (type A) transistors
(September - December)

General Comments: Generally speaking, no deficiencies of material, equipment or personnel have hindered the progress of the contract with the exception of the need that developed midway through the contract for very lightly donor-doped gold wire. Considerable reluctance was found on the part of commercial suppliers to fabricate donor-doped gold of the type found necessary for making transistors with the desired characteristics. Significant progress, however, has been made by the combination of de-doping techniques developed here and specially doped gold wire which has been secured from commercial sources.

Conferences and Communications: During the course of the contract, several conferences were held between Mr. Bowe, the Air Force Project Engineer monitoring the contract, and Mr. Langevin, Project Manager for Transistor Products, Inc. The first of these conferences, held in late July, was intended for general orientation and at that time our plans for work on the contract were presented to Mr. Bowe. A subsequent meeting in late September was attended by Messrs. Bowe, Ryan and Mueller from Air Force Cambridge Research Centerand Messrs. Langevin, Richards and Humez from Transistor Products, Inc. This September meeting served to review progress of the contract up to that date and at that time an outline was given of the work planned up to the termination date of the contract.

Mr. R. Nelson, Comptroller of Transistor Products, Inc., accompanied by Mr. Langevin, visited Mr. Nadile, the Air Force Contract Officer, to discuss general aspects of contract language, and audit policy etc.

On December 2, 1953, Mr. Bowe and Lt. Rutherford from Air Force Cambridge Research Center visited Transistor Products, Inc. and a general conference was held covering all phases of the work done on the contract. Transistor Products, Inc. was repr3sented at this conference by all of the senior project people previously listed. At the same time, Mr. Bowe was provided with a sample of fifty-four gold bonded transistors which had been made by the techniques developed during the contract period. An additional fifty-seven gold bonded transistors have been supplied at the termination of the contract. In addition twenty-five sample face to face transistor assemblies have been supplied to the sponsoring agency for their expermmental use. Finally, a sample of twenty to twenty-five symmetrical gold bonded transistors have also been supplied to the sponsoring agency. These transistors, although not specifically called for by the contract, are considered of considerable theoretical and practical interest, particularly for discriminator applications in the megacycle region. During the course of the contract, a proposal was submitted to Mr. Bowe outlining a development program for a "junction-like" transistor which will give useful gain at frequencies of the order of ten megacycles. This proposal, which was submitted on 28 September, grows, naturally, out of and, we believe, is the logical next step to follow, work done on the present contract on "point contact" gold bonded transistors. The proposal contemplates a program somewhat more general in scope than the present contract to permit a study of materials other than gold in the bonding process and it is further proposed that the decision as to the specifications of the transistors to be fabricated be deferred until the completion of a preliminary study phase. It is believed that by such means the most rapid progress can be made toward useful end devices and that this procedure will provide the fullest possible exploitation of bonding techniques.

REVIEW OF THE DEVELOPMENT

Problems: The course of the development work on the present contract can most readily be outlined by discussing the work done on the following nine major problems which have arisen in the course of the contract work:

1. Theory of alpha in two-sided transistors.
2. Theory of frequency cutoff.
3. Study of gold bonding techniques.
4. Methods of obtaining thin base layers.
5. Humidity studies.
6. Methods for obtaining lightly donor-doped gold wire.
7. Fabrication of experimental transistors.
8. Methods of packaging two-sided units.
9. Special apparatus development
    a. Airbrasive unit
    b. Gold bonding set
    c. Noise figure measuring set

Methods of Attack: Significant progress has been made on all of the above problems with the exception of 8) Methods of packaging 2 sided units. The theoretical problems 1) and 2) have been solved for the case where diffusion is the only active transport mechanism. Idealized geometry has been utilized as much as possible to make the problems tractable although it is believed that the idealization still retains the relevant features of the geometry of the actual devices. Details of these theoretical studies will be found in Appendix A.

The gold bonding study, 3) has been carried out primarily on diodes. This has seemed to be the best way to minimize the number of active variables in the problem. Experiments have been made primarily to obtain a comparison of "resistance bonding", in which the gold wire, initially separated from the germanium is advanced until an arc strikes effecting the bond. Details of this work will be found in Appendix B.

Theory indicates and experience confirms that in order to obtain a high α and high α cut-off frequency in the two-sided units it is necessary to have base layer thicknesses of the order of .001" or less. Attempts to secure base thicknesses of this order by masking and etching and by lapping either fail or produce structures so fragile that they cannot be handled. This problem has, however, been very adequately solved by the use of an S. S. White Airbrasive unit. With this machine it is possible to bore wells or troughs in germanium wafers in such a way that the thin section is essentially supported by thick material and hence can be handled with ease. Base layers of less than .001" can readily be obtained by this process.

Concurrent with the development work on gold bonding and gold bonded transistors, a limited study has been carried on to determine the effects of humidity on gold bonded contacts. At the initiation of the contract there had been some hope that gold bonded contacts by virtue of the intimate contact attained between the gold and the germanium might be less sensitive to humidity effects than pressure contacts. Unfortunately, humididty studies on gold bonded contacts have not supported this hope. Generally speaking, the rectifying gold bonded contacts are similar to pressure contacts in the adverse effects of high humidity; however, some success in minimizing these effects has been had with special surface treating agents.

Details of the work carried out in this humidity study will be found in the Attached Appendix C.

As work on the contract progressed and variously doped gold wires were studied experimentally it became increasingly evident that transistors with characteristics as contemplated in the contract could not be obtained unless it was possible to obtain donor doped gold wire with extremely low concentrations of the doping agent. Initial efforts to secure antimony doped gold with doping percentages ranging down to .001% or less from commercial sources were not successful. Consequently, several approaches were utilized in an attempt to fabricate such wire ourselves. The first approach was based on the use of commercially available 1% antimony-doped wire. Since the vapor pressure of antimony is higher than that of gold, it should be possible to "de-dope" such gold wire to any desired extent by heating the wire in a vacuum and essentially boiling off some of the antimony.

Experiments on this de-doping enabled us to secure small samples of de-doped wire with which transistors of desirable characteristics could be fabricated. However, because of inhomogeneity in wire doping and strain configuration, this procedure has not proved practical. Consequently, doping was attempted by using essentially pure gold which had been dipped in various antimony solutions. Results obtained by this method were promising but were abandoned in favor of a method which consisted of moving the gold wire continuously through a furnace. In the meantime, we were successful in obtaining antimony doped gold wire in which the antimony dope was supposed to be .01%. With this wire, moderate success has been had in transistor fabrication but the desirability of still lighter doping has led us to continue our de-doping efforts to the termination of the contract. Details of the doping studies will be found in Appendix D.

Experimental gold bonded transistors of two general types have been made: The first of these, the "one-sided" or Type A unit, is essentially a conventional Western Electric cartridge type point contact transistor in which the phospher bronze and beryllium copper whiskers have been replaced by variously doped gold wires of .002" to .003" in diameter. A more unconventional but more interesting type of device is the 2 sided or "face to face" unit in which emitter and collector wire, are bonded to opposite faces of the germanium wafer. These units are assembled on 3 pin glass-metal headers similar to those being used by many manufacturers for junction transistors. A limited attempt has also been made to fabricate the one sided units on the three pin glass metal headers. A detailed discussion of the transistor fabrication will be found in Appendix E.

In addition to the problem of building experimental transistors of the face to face and one sided type for the evaluation of germanium resistivity, various doping agents, etc., it has been necessary to consider the problem of packaging the gold bonded transistor into structures that are mechanically rugged, stable, resistant to humidity, etc. This has been adequately accomplished on the one-sided units by the use of the Type A cartridge. The two-sided units however have proved to be too fragile for packaging by any means so far tried. This fragility is primarily attributable to the fact that with the donor doped gold wire sofar used for the collector it is not possible to obtain mechanically strong bonds and at the same time secure transistor characteristics in the desired range. In addition to the point contact-like transistors called for by Exhibit A of the contract a limited number of symmetrical transistors of the face to face type have been fabricated using 1% gallium doped gold wire for the emitter and collector. Samples of these units have been supplied to the sponsoring agency.

Special Apparatus and Equipment

Mention has already been made of the S. S. White Airbrasive unit. This machine, made by the S. S. White Dental Mfg. Co., N. Y. C., has been indispensible in cutting wells in germanium wafers to obtain thin base sections. Considerable control of the cutting process has been obtained utilizing a timer to give short (.01 to 1 second) blasts of abrasive. Empirically, a number (5-10) of short blasts of equal duration seems to give the best control of the cutting process.

To facilitate the bonding and testing of the experimental "face to face" transistors a standard gold bonding pulser has been modified to permit bonding and approximate measurement of α and r_c in the same set.

In order to obtain noise figures on the experimental transistors fabricated in the course of the contract, and on the samples supplied to the sponsoring agency, a transistor noise figure measuring set has been constructed. Details of the gold bonding set and transistor noise measuring set are contained in the Appendix F.

Status at Termination of Contract

Theory: Calculation of the maximum attainable α in a face to face transistor suggest that a limiting value of about $\alpha = .8$ is the best that can be expected for collector and emitter of equal cross section and acceptor doping in both emitter and collector. Cut off frequency calculations, assuming diffusion to be the only active transport mechanism suggest that 10 megacycles can be attained for base layer thicknesses of the order of .001". The fabrication of experimental transistors, as will be described subsequently, has provided general confirmation of these results.

Gold Bonding Studies: The work done to study the comparative behavior of resistance versus "arc" bonding has been very inconclusive. Results obtained by the arc technique have not at any time been significantly better than those obtained with conventional resistance bonding techniques. On this account further work on this problem was discontinued.

Thin Base Layer: As already mentioned, thin base layers ranging down to .001" can be easily obtained with the Airbrasive unit. While no specific reproducibility studies have been made, it is our strong impression that the base thickness can be controlled to about .0005" in this process.

Humidity Studies: The basic objective of the humidity studies has been to ascertain whether gold bonded contacts exhibit in the presence of moisture any characteristics significantly different from those observed with conventional pressure contacts. A general discussion of results in Appendix C shows that gold bonded contacts are unfortunately no better in this regard.

Methods for Obtaining Lightly Donor Doped Gold Wire: Three methods have been utilized for the local preparation of lightly donor doped gold wire:

1. De-doping antimony doped gold wire by passing current through the wire in vacuum
2. Doping "pure gold wire by dipping into various aqueous antimony solutions.
3. De-doping antimony doped gold wire by moving it continuously through a resistance furnace in air.

The first of these techniques has proved unsatisfactory due to marked inhomogeneity in doping level and wire diameter resulting from the process. The dipping technique, while promising, has been abandoned in favor of the third, continuous processing technique. By this latter means it has been possible after considerable experimentation to de-dope antimony doped gold wire in relatively homogeneous fashion without introducing noticable variations in wire diameter.

Fabrication of Experimental Transistors: By utilizing the techniques developed in the course of the development work it has been possible to fabricate gold bonded transistors as contemplated in the contract. Experimental transistors have been of two types, a one sided unit similar structure to a conventional "Type A" point contact transistor and a two sided or "face to face" unit which offers structural and electrical advantages. 110 samples of the one sided units together with complete data have been supplied to the sponsoring agency. In addition two sided transistors, of a special "symmetrical" type have been supplied in sample quantities. These units are characterized by the fact that they have an emitter and collector with nearly identical electrical characteristics.

Packaging of Two Sided Units: Gold bonded transistors of the type contemplated in the contract require the use of suitably donor doped collectors. Very light bonding is required with such wire to obtain the desired electrical characteristics. In the two sided units the fragility of this bond has made it impractical to "package" these units satisfactorily. As a consequence it has not been feasible to supply samples of this second type of gold bonded transistor before the termination of the contract.

Special Apparatus Development: No difficulties were encountered in modifying a gold bonding pulse set and fabricating a transistor noise figure measuring set for the purposes of this contract. The equipment has been used in the course of the work and performs satisfactorily.

SUMMARY OF RESULTS

During the course of development work it has been established that transistors of the type contemplated in the contract can be made using 1% gallium or indium doped gold wire for the emitter and lightly antimony doped gold wire for the collector. It has been determined that the preferred antimony doping is less than .01%. Considerable work has been done on specific techniques for preparing antimony doped wire with the desired doping level. Bonding techniques have been developed for obtaining transistors with the desired characteristics. Transistors have been built using the methods and materials developed in the course of the contract and a sizable sample together with data supplied to the sponsoring agency. In addition it has been possible to supply samples of a "symmetrical" transistor which, although not contemplated in the present contract, is considered of considerable theoretical and practical interest.

RECOMMENDATIONS

On the basis of the work carried out to bring the contract to a successful conclusion it has become evident that in order to fully exploit the knowledge and techniques developed to this point it would be desirable to undertake further development work in directions outside the scope of the present contract. In particular, the following specific recommendations appear to be warranted:

1. Evidence has accumulated that the process of gold bonding may well involve primarily a recrystallization process from the germanium-gold eutectic. Such a process would be critically dependent upon the nature of the current pulse utilized in the bonding operation. While the bonding equipment used in the course of the present contract has made it possible to fabricate satisfactory transistors the possibility exists that much more elaborate bonding techniques affording full control of the bonding pulse may permit more adequate control of the recrystallization phase of the bonding operation and significantly improve the yield in the fabrication of gold bonded transistors.

2. The techniques developed in the course of the present contract for obtaining lightly antimony doped gold wire for collector use have been effective on the practical level. It would be desirable to determine quantitatively the optimal doping level. In addition the present techniques for de-doping leave the gold wire extremely soft. While this interposes no real barrier to the fabrication of gold bonded transistors such as have been made for the present contract, should such transistors be required in large quantities it would be helpful to develop suitable means for hardening the wire without upsetting the doping level.

3. It will have been noted in the preceeding discussion that it was not considered feasible to adequately package the two sided gold bonded transistors because of the fragility of the collector bond. While the one sided samples supplied are considered adequate there are mechanical and electrical advantages to the two sided units which would make it desirable to undertake the necessary packaging development to learn how to adequately package the two sided units.

Appendix A

Cut-Off Frequency Calculation

Problem: To determine the cut-off frequency for the transport of holes from emitter to collector assuming the transport to take place solely by diffusion.

Solution: For this problem a one-dimensional geometry should be adequate for determining the correct order of magnitude of the cut-off frequency.

The relation between current density, j_p, and hole concentration, p, in the one dimensional case is:

$$j_p = -kT\mu_p \frac{dp}{dx} \qquad (1)$$

where μ_p is the hole mobility. In the steady state j_p must be independent of x if recombination can be neglected so we may re-write (1) as

$$dp = -\frac{j_p}{kT\mu_p}dx \qquad (2)$$

where the coefficient of dx is a constant. The boundary conditions are: hole current j_p introduced at the emitter (x = 0); hole current j_p removed (i.e. p = 0) at the collector (x = L). The solution of (2) is therefore

$$p = \frac{j_p}{kT\mu_p}(L - X) \qquad (3)$$

If recombination is considered, the continuity equation must be used:

$$\operatorname{div} j_p = -\frac{p}{\tau_p} \qquad (4)$$

where τ_p is the lifetime of holes in the germanium, combining equations (1) and (4) gives

$$\frac{dj_p}{dx} = -\frac{p}{\tau_p} = -kT\mu_p\frac{d^2p}{dx^2} \tag{5}$$

The solution of this equation must have the form:

$$p = Ae^{-ax} + Be^{ax} \tag{6}$$

Differentiation gives

$$a^2 = \frac{1}{kT\mu_p\tau_p} \tag{7}$$

while applying the boundary condition p = 0 at x = L gives:

$$\frac{A}{B} = -e^{2aL} \tag{8}$$

and the boundary condition $\left.\frac{dp}{dx}\right|_{x=0} = -\frac{j_0}{kT\mu_p}$ gives

$$A = \frac{j_0}{kT\mu_p a}\cdot\frac{1}{(1+e^{-2aL})} \tag{9}$$

The solution is therefore

$$p = \frac{j_0}{kT\mu_p a}\left[\frac{e^{-ax}}{1+e^{-2aL}} - \frac{e^{ax}}{1+e^{2aL}}\right]$$

(10

If $aL \ll 1$ this reduces to

$$p = \frac{j_0}{kT\mu_p a}\left[a(L-x)\right] \qquad (11')$$

which is identical with the solution obtained by neglecting recombination. Since τ_p may be $> 10^{-4}$ sec for a good single crystal of germanium (cf. Shockley, Electrons and Holes in Semiconductors, p. 68) and since $kT\mu_p$ = 44 cm^2/sec for germanium at room temperature (Conwell, Proc. I.R.I., Nov. 1952)

$$aL = \frac{L}{(kT\mu_p\tau_p)^{1/2}} < \frac{L}{(44\times10^{-4})^{1/2}} \simeq \frac{L}{.07} \qquad (12)$$

so recombination can be neglected for $L \ll 0.07$ cm.

In order to determine the cut-off frequency, a solution of the time dependent equation,

$$\frac{\partial p}{\partial t} = kT\mu_p \frac{\partial^2 p}{\partial x^2} \qquad (13)$$

is required. If a periodically varying current,

$$j_p = j_{op}\sin\omega t = I_n\left(j_{op}e^{i\omega t}\right)$$

where I_n ( ) indicates "the imaginary part of ( )", flows at $x = 0$, the boundary conditions are

$$\left.\frac{dp}{dx}\right|_{x=0} = -\frac{I_n\left(j_{op}e^{i\omega t}\right)}{kT\mu_p} \qquad (14)$$

and p = 0 at x = L. Assuming a solution of the form

$$p(x,t) = I_n\left(u(x)\,e^{i\omega t}\right) \qquad (15)$$

we have

$$i\omega\, u(x) = kT\mu_p \frac{d^2u}{dx^2} \qquad (16)$$

The function u (X) must have the form

$$u(x) = C\,e^{bx} + D\,e^{-bx} \qquad (17)$$

so that

$$i\omega = kT\mu_p b^2 \qquad (18)$$

or

$$b = \left(\frac{\omega i}{kT\mu_p}\right)^{1/2}$$

Application of the boundary conditions gives

$$\frac{-j_{op}}{kT\mu_p} = b(C-D) \qquad (19)$$

and

$$C e^{bL} + D e^{-bL} = 0 \qquad (20)$$

$$\frac{D}{C} = e^{2bL} \qquad (21)$$

$$C\left(1+e^{2bL}\right) = -\frac{j_{op}}{kT\mu_p b} \qquad (22)$$

$$D\left(1+e^{-2bL}\right) = \frac{j_{op}}{kT\mu_p b} \qquad (23)$$

$$u(x) = -\frac{j_{op}}{kT\mu_p b}\left[\frac{e^{b(x-L)} - e^{-b(x-L)}}{e^{-bL}+e^{bL}}\right] \tag{24}$$

$$j_p(x) = j_{op}\left[\frac{e^{b(x-L)} + e^{-b(x-L)}}{e^{-bL}+e^{bL}}\right] \tag{25}$$

For $bL \ll 1$, this becomes

$$j_p(x) = j_{op} \tag{26}$$

(which is identical with the steady state solution.)

$$j_p(x,t) = j_p(0,t) \tag{27}$$

for $bL < 1$

$$j_p(x) \approx j_{op}\left[\frac{1+\frac{1}{2}[b(x-L)]^2}{1+\frac{1}{2}(bL)^2}\right] \tag{28}$$

$$j_p(x) \approx \frac{j_{op}}{1+\frac{1}{4}\left(\frac{\omega L^2}{kT\mu_o}\right)^2}\left[1 - i\cdot\frac{1}{2}\frac{\omega}{kT}\frac{L^2}{\mu_p}\right] \tag{29}$$

Therefore at $x = L$

$$j_p(x,t) = \frac{2 j_{op}}{1+\frac{1}{4}\left(\frac{\omega L^2}{kT\mu_p}\right)^2}\left[1 + i\cdot\frac{1}{2}\cdot\frac{\omega}{kT}\cdot\frac{L^2}{\mu_o}\right]e^{i\omega t} \tag{30}$$

and are out of phase, where the approximation is valid to within 1%, for

$$\left(\frac{\omega}{kT\mu_p}\right)^{1/2} L = 1$$

Evidently the magnitude of the current at x = L is then 20% less than the current at x = 0, and its phase lags the other by about 27°. Thus the order of magnitude of the cut-off frequency is

$$\frac{\omega}{2\pi} = \frac{kT/q\,\mu_p}{2\pi L^2} = \frac{44}{2\pi L^2} \qquad (31)$$

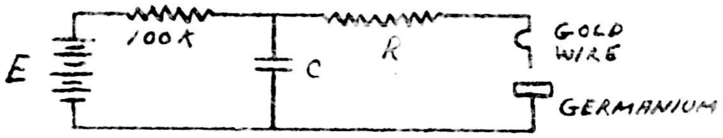
$$f = \frac{7}{L^2} \cong 7\ mc \qquad L = 10^{-3}\ cm$$

Appendix B

Study of Bonding Techniques

Introduction - At the beginning of the project it was suggested that bonding performed by establishing contact between molten gold and molten germanium might result in bonds superior to those achieved by first making contacting between gold wire and germanium and then passing current through the contact.

The general scheme suggested is shown below:



On moving the gold toward the germanium an arc will be established through which the condenser C will be discharged. It was hoped that by varying C, R, and the magnitude and polarity of E some control of the bonding process could be obtained.

Possible Advantages of "Arc" Bonding

a) Possibly greater uniformity of bonds could be achieved since the bond should be largely independent of the initial condition of the germanium and gold surfaces. In the method presently used (resistance bonding) variation in the resistance of the initial contact may contribute to the non-uniformity of the resulting bond.

b) Variation of C, R, E, and the polarity of E can be used to preferentially heat either the gold or the germanium - this independent control is not available with resistance bonding where the heat is developed at the gold-germanium interface. It is possible that bonds of greater mechanical strength could be made by this method.

Preferential Heating of Gold or Germanium - The energy dissipated in the gold and in the germanium can be calculated if the arc is assumed to have a fixed voltage drop, E_{arc}

$$\text{Energy in Germanium} = \int_0^\infty i^2 R_s \, dt$$

where R_s is the spreading resistance of the germanium. It has the theoretical value

$$R_s = \frac{\rho}{8r}$$

Here ρ is the resistivity in ohm cm and r is the effective radius of the contact in cm (say 10^{-2} cm).

Similarly, (when the gold is used as the anode)

$$\text{Energy in gold} = E_{arc} \int_0^\infty i \, dt$$

Substituting, we have

$$\text{Energy}_{\text{gold}} = R_s C (E - E_{arc})^2$$

and

$$\text{Energy}_{\text{germanium}} = E_{arc} (E - E_{arc}) C$$

The fact that either the gold or the germanium can be preferentially heated can be demonstrated by computing the ratio

$$\frac{E_n(\text{GOLD})}{E_N(\text{GER})} = 2 \frac{E_{arc}}{E - E_{arc}} \cdot \frac{R + R_s}{R_s}$$

Thus at a fixed value of C the fraction of the total energy which heats the gold can be controlled by varying the initial voltage on the condenser E and the series resistance R. It is thought that this degree of control is not available with conventional resistance bonding.

The above approximate formulae are not sufficiently accurate for quantitative design of a bonding method, since in addition to the assumption of a fixed arc voltage drop, we have neglected the temperature dependence of the spreading resistance and the arc characteristics.

Magnitude of Electrostatic Forces - Originally it was thought that the electrostatic forces between the gold and germanium would be an important factor in establishing the mechanical bond. Analysis shows that for the range of voltages used the arc is always initiated at distances much larger than those where the electrostatic forces would become appreciable. The electrostatic forces are sufficiently great to close the gap when the separation is $(4KE^2/S)^{1/3}$ cm where E is the voltage, K is a constant related to the electrical capacity of the gold-germanium system ($K = Cd$ where d is the separation), and S is the spring constant of the mechanical system supporting the germanium and gold point. For $E = 100$ volts and estimated values of K and S for the system used, electrostatic closure of the gap would be expected at distances of the order 5×10^{-4} cm. However, the arc starts when the separation is $\frac{E}{\gamma}$ where γ is the breakdown field strength (about 10^4 volts/cm) which gives 10^{-2} cm for the striking point of the arc. Accordingly, the arc starts long before the point is close enough for electrostatic forces to be of sufficient magnitude to aid in establishing contact.

Miscellaneous Calculations

A) - The energy required to bring a segment of gold wire of diameter .003" and length = .003" to the melting point is approximately 2×10^{-4} joules.

B) - The energy required to raise the temperature of an equal volume of germanium to the melting point is approximately the same.

C) - The energy available from a 1 uf condenser charged to 100 volts is 5×10^{-3} joules. Therefore, getting sufficient energy is not a problem.

D) - The time required for a heated region of gold wire .003 inches long to lose half of its heat by conduction is approximately 6 milliseconds.

E) - Using D above and the breakdown strength of air, the gold point must be moved toward the germanium at a velocity of greater than 2 cm/sec in order to make contact before the gold is cooled.

Experimental Results

A. Polarity Effect - It has been verified experimentally that more energy is dissipated in the gold when it is used as the anode of the arc. For E = 100v, R = 0, and C = 6 uf. None of the gold melts when it is used as the arc cathode. On reversing polarity, quite a bit of gold is vaporized. Under these conditions a crater is vaporized in the germanium for either polarity, presumably because the heating in the germanium is largely due to I^2R loss in the spreading resistance.

B. Optimum Bonding with Slow Velocity of Approach - Bonds were attempted between etched germanium of 5 ohm cm resistivity and 1% gallium doped gold wire with the following results. The gold was brought up to the germanium slowly in these experiments.

1.) At low voltages, (E = 22v) with R = 0, bonds can be made with the gold as the anode. Increased mechanical strength and increased reproducibility were observed with increasing capacity from 1 to 10 uf. However the strength and reproducibility were not good under any conditions.

2.) With E = 45 volts, R = 0, Au +, C = 2 to 10 uf, good bonds were achieved with fair consistency. Microscopic examination showed both gold and germanium had melted.

3.) With E = 90 volts, R = 0, Au +, C = 2 uf or more, no bond was made although a large ($3x10^{-2}$) cm dia.) crater was melted in the germanium and the gold was obviously melted. Evidently, the gold never came in contact with the germanium. Presumably, using a greater velocity of approach would do better here. The introduction of series resistance made it possible to achieve bonds although the reproducibility was not nearly as good as in 2) above.

4.) At higher voltages large quantities of gold were vaporized and no bonds achieved with R = 0.

C. Some bonds were made using a higher velocity of approach (about 5cm/sec) with fair to good mechanical strength and reproducibility. However, this method did not appear suitable for mass production - particularly at the narrow point spacings required for transistors.

D. Electrical characteristics of diodes made by these arc bonding techniques were checked and found to be essentially similar to those obtained on diodes made by resistance bonding.

APPENDIX C

EFFECTS OF HUMIDITY ON BONDED GOLD-GERMANIUM CONTACTS

In connection with the development of gold bonded transistors it has seemed important to undertake a limited program to determine the effects of humidity on bonded gold-germanium contacts and to make a cursory search for effective means of reducing these effects.

The most important effect of humidity on bonded gold-germanium contacts is a marked decrease in reverse resistance which occurs when moisture comes into contact with the bond. The effect, similar to that observed for pressure contacts is shown in the accompanying Figure in which the value of reverse current at ten volts is plotted against the percentage of units having less than that value for ten gold bonded diodes on successive days of humidity cycling. Although these units were protected by encapsulating in a glit filled phenolic cartridge, the gradual deterioration of the reverse characteristics is evident.

A limited amount of work has been undertaken in an effort to prevent or at least to retard this deterioration. One approach has involved an attempt to reduce the sensitivity of the bond itself to moisture, while a second approach has sought means of preventing the penetration of moisture to the sensitive region.

In the first part of the study, elementary, unencapsulated diodes have been utilized. It has been found that the response of a bare diode to water vapor depends critically on the treatment which the germanium wafer receives prior to bonding. In particular, diodes which are not washed after the wafer is soldered to the ohmic lead respond immediately to the presence of water vapor whereas diodes which have been washed with a detergent such as "Alconox" do not. Surprisingly, a group of diodes washed with detergent exhibited no significant deterioration of reverse characteristics during a three day exposure to a relative humidity of approximately one hundred per cent. at 70°C. These diodes, however, regained their sensitivity to water vapor after a drop of deionized water had been placed at the bond and allowed to evaporate. Perhaps the most surprising feature is that this water drop treatment improved both the forward and reverse diode characteristics in many cases.

These observations suggest the possibility of finding a surface treatment which will indeed reduce the sensitivity of the active part of the diode to moisture. A number of possibilities, for example, the hydrolysis of water repellent chlorosilanes onto the surface of the germanium, could be tried.

Little has been done on the second phase of the study, concerned with keeping moisture away from the sensitive region. Little or no improvement has been achieved by using a variety of resins or rubber coatings although the use of a silica filler in an epoxy resin shows some promise. The most successful moisture barrier studied is achieved by enclosing a plastic beaded diode in a glass tube filled with dessicant and sealing the ends of the tubes with an epoxy resin. Presumably, this technique of a double seal against moisture could also be applied to transistors.

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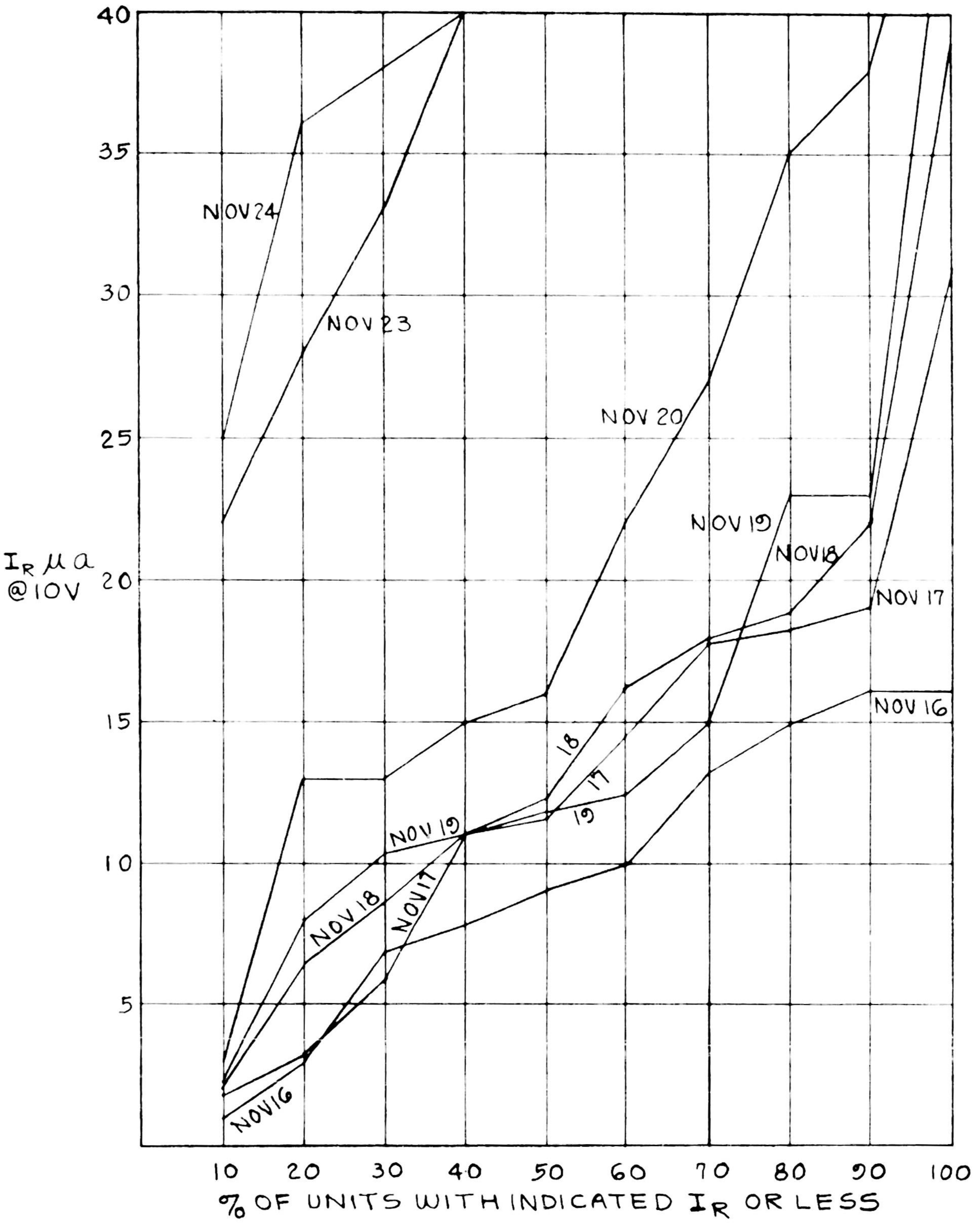


REVERSE CURRENT DETERIORATION WITH HUMIDITY FOR GOLD BONDED DIODES

APPENDIX D

DOPING STUDIES

Initial experiments were carried out on face to face gold bonded transistors using .003" gold wire doped as follows:

EMITTER DOPING	COLLECTOR DOPING
None	None
1% Ga	1% Ga
5% In	1% Sb
1%In	1% Sb
1% Ga	1% Sb

These initial studies were carried out on units with a nominal .002" point spacing, utilizing germanium ranging in resistivity from 3 to 30 ohm cm. Measurements of the small signal parameters of the resulting transistors established the following:

1. Units with 1% Gallium doped emitter and collector exhibit junction like properties with the α always less than 1. Values of .5 to .7 are typical. Collector impedances of 10 to 20 thousand ohms are readily obtainable with α cutoff frequencies as high as 7 megacycles and power gains of 15 db. or more.
2. No difference in emitter characteristics could be discerned between the 1% gallium and 1% indium doping. While the 5% indium doping also affords satisfactory emitter characteristics some difficulty is experienced in bonding successfully when using this wire.
3. Antimony doping (presumably arsenic would do as well) of the collector is essential if current gains greater than one are to be obtained. While 1% antimony doping makes it possible to obtain

current gains as high as 5 to 6, these high current gains are always accompanied by collector impedances of the order of a few hundred ohms. This is interpreted as indicating that the antimony doping level is much too high.

Following the discovery that the donor collector doping required for satisfactory operation is less than 1% efforts were made to secure less heavily doped wire from commercial sources. Because there was initially no readily available commercial source of antimony doped gold wire in the doping levels desired a program was undertaken to devise means of providing wire of the desired characteristics locally. The first approach was based on the fact that the vapor pressure of antimony is much higher than that of gold and that therefore it should be possible to effectively "boil out" some of the antimony by heating 1% antimony doped gold in a vacuum. Initial studies of this process confirmed that the antimony could indeed be "boiled out" of antimony doped wire by heating in vacuum to temperatures of approximately 600° Centigrade for times of the order of twelve to twenty-four hours. Although the doping levels attained by these methods gave improved results in transistors, other difficulties arose in connection with this process. Specifically, the heating (a) destroyed the temper of the wire and thus made it difficult to handle in the transistor assembly operation and, more importantly, (b) relieved local strains (due presumably to the wire-drawing operation) thereby leading to considerable non-uniformity in both doping level and the wire diameter.

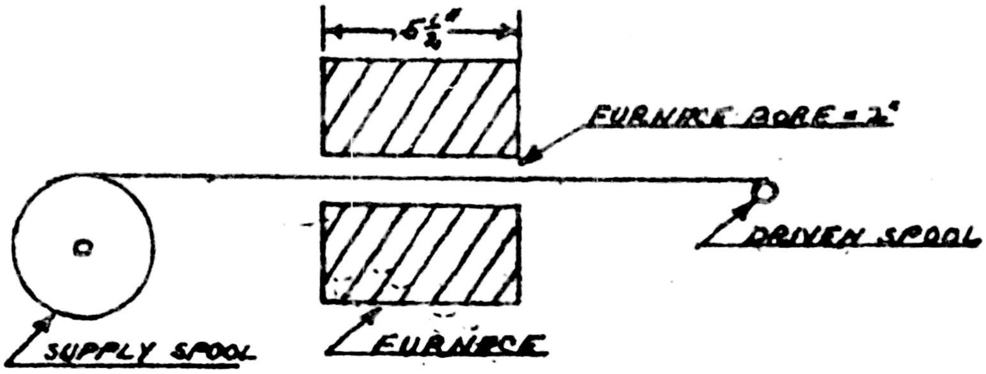
Because of these difficulties another approach was explored, the introduction of antimony dope onto "pure" (99.99%) gold wire by dipping the wire into an aqueous solution containing antimony. At first, solutions of $SbCl_3$ were used but the results were found to be very variable. This was traced to the fact that $SbCl_3$ reacts with water to form SbOCl which in turn is essentially insoluble but which forms a colloidal suspension in water. Thus, the antimony strength of the resulting "solution" is very dependent on time and methods of handling. To obviate this difficulty solutions were prepared using antimony-potassium-tartrate. This forms a true solution in water and it was found that 99.99% gold wire dipped in such a solution (10 mg of K-Sb-tartrate to 3p cc of distilled water) yielded, when bonded, results very similar to 1% Sb-doped gold wire.

The reproducibility was at first poor but became quite good upon adding to the above solution about 0.1 gram of "alconox" detergent which apparently had the effect of cutting through residual die-lubricants etc. on the surface of the wire.

At this stage in the investigation, we were fortunate in obtaining some 0.01% antimony doped wire from a commercial supplier and the dip-doping was discontinued in favor of this predoped wire which was felt to be more reliable and more easily handled in assembly. A number of one sided transistors were fabricated using this wire. With this lightly doped wire it proved possible to obtain transistors meeting the contract specifications. Difficulty was still, however, experienced with the strength of the bond with the result that de-doping studies were resumed using the .01% antimony doped wire as a starting materially.

This time the problem was approached via the "boiling out" technique but with the differences that the "boiling out" was carried out in air instead of in a vacuum and was accomplished by drawing the wire continuously through a 900°C resistance furnace. This continuous operation appears to provide good uniformity of doping level and little alteration of the wire diameter contrary to previous experience in the vacuum de-doping operation. The successful operation of this de-doping system was only obtained in the very last stages of the contract and while experimental transistors confirm its value in obtaining the desired transistor characteristics along with a mechanically strong bond it arrived too late to be utilized in the samples supplied to the sponsoring agency.

A sketch of the dedoping furnace is shown below:



Typical operation of the furnace involved the following parameters:

Furnace temperature at center - approximately 900°C.
Pull Rate - 1.8"/hour
Gold Wire - .003" diameter, .01% Sb Gold

The extremely slow pull rate could be obviated by modifying the above structure to provide for the gold wire to traverse the furnace a number of times.

APPENDIX E

FABRICATION OF EXPERIMENTAL TRANSISTORS

Experimental transistors of two types have been fabricated. These have been one sided units in a cartridge similar to the Western Electric Type A and a two sided unit constructed on an in line transistor base as tentatively proposed by the RETMA. It has been found that either 1% gallium or 1% indium doped gold wire .002" to .003" in diameter makes a very satisfactory emitter. Typical diode characteristics of the emitters are given in the attached data sheets. For the collector 1% and .01% antimony doped gold wire has been used. Other experimental units have been fabricated using "de-doped" gold obtained by methods described in Appendix D. While the optimal de-doping has not been quantititively determined experiments using .01% antimony doped gold wire .003" in diameter as starting material have established approximately 1.8"/hour as a satisfactory pull rate in the continuous dedoping process. Such dedoped wire gives promising results in the fabrication of transistors with

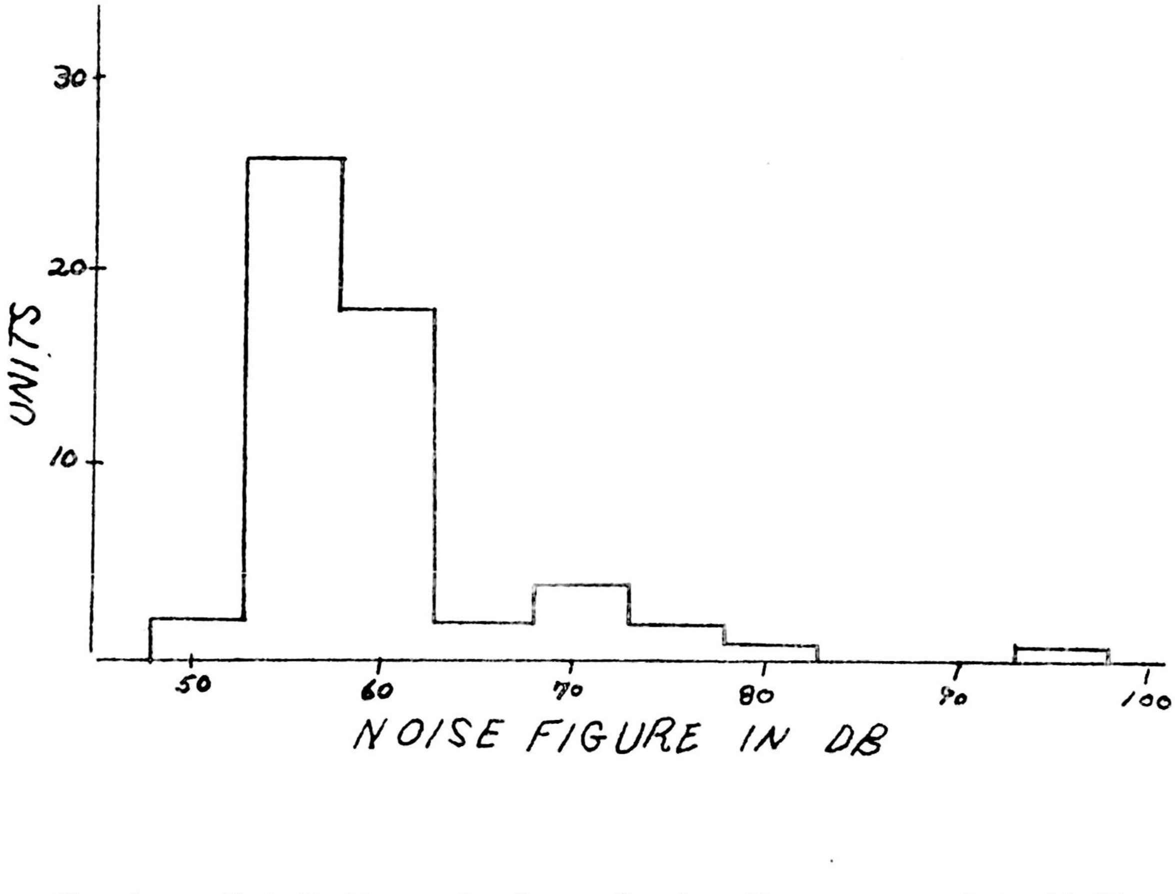
$\alpha > 2, r_{22} > 10K\,\Omega$ and α cutoff > 10 mc.

The resistivity of the germanium has been varied in the range from 5 to 20 ohm centimeters without materially affecting the characteristics of experimental units. There are, however, some indications in the accompanying data that a material resistivity in the vicinity of 10 ohm centimeters may give somewhat better results.

One hundred and tem sample transistors of the one sided type have been fabricated, tested, and supplied to the sponsoring agency. The test data on these units will be found in the following pages together with an information sheet which shows the emitter and collector materials and the germanium resistivity used in each sample transistor.

It should be emphasized that the sample units supplied to the sponsoring agency have been selected with a view to illustrating the range of transistor characteristics which can be obtained by the gold bonding technique. It is, therefore, only units later in the series (incidentally the latest chronologically) which meet the contract specifications.

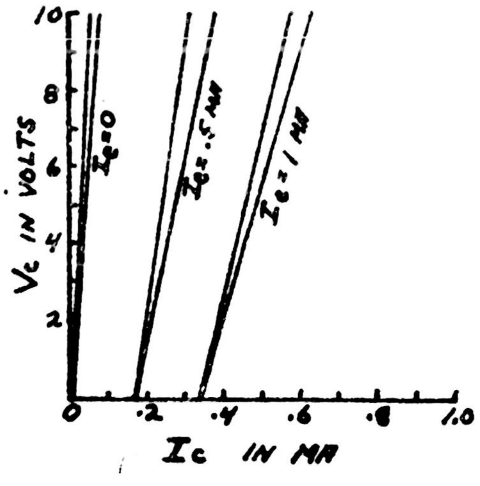
In addition to the measurements tabulated in the succeeding pages, noise figure measurements have been made on units 55 through 110. The following histogram gives the result of these measurements. The noise figure here is measured at 1000 cycles/second for a nominal one cycle bandwidth.



The above distribution and values of noise figures are substantially similar to those obtained from measurements on conventional point contact transistors. The high noise figure of these transistors is not understood but may be associated with the fact that the collectors were only very lightly bonded.

Noise figure measurements were also made on a number of units on which emitter and collector current were varied. There is observed a noticeable trend toward increasing noise figure with increasing emitter current. This trend is of the general form, noise figure = $F + \gamma I_e$. $F = 55$ db and $\gamma = 2$ db /MA are representative of the valves observed over the range, $.5 \doteq I_e \doteq 4$ MA. Relatively little dependence on the value of V_c was observed.

During the course of the development of a few "symmetrical" transistors were constructed. These units have emitter and collector wires of 1% gallium doped gold .003" in diameter and utilize a germanium wafer with approximately 5 ohm centimeter resistivity. The units are so bonded that emitter and collector characteristics are made as nearly identical as possible. As a result either gold wire can be used as the emitter or collector and the units are true symmetrical transistors. Typical characteristics of the units are $.5 \leq \alpha \leq .7$, $r_{22} > 10 K\Omega$, α CUTOFF > 5MC. While these units are not specifically called for by the contract a sample of ten units has been supplied to the sponsoring agency as a matter of general interest. Typical static characteristics of these symmetrical units are shown in the following figure:



Transistor No.	Resistivity Ohm Cm.	Emitter Wire	Collector Wire
1,79	15	.003" 1% Ga	.003" 1%Sb
77,78	5	.002" 1% Ind.	.003" 1%Sb
80,81	9	.003" 1%Ga	.003" 1%Sb
82	15 - 20	.002" 1%Ind.	.003" 1%Sb
111	10	.002" 1% Ind.	.003" 1%Sb
83,84	7	.002" 1% I	.003" 1%Sb
85,86,87,88,89.	8	.002" 1% I	.003" 1%Sb
23, 90	10	.002" 1% Ind.	.003" 1%Sb
3,7,9,12.15,29, 30,91,92,93	11	.002" 1% Ind.	.003" .01%Sb
11,12,13,14,15 16,17,18,19,20 99,100,101,102, 103,104,105,106 21,22,23,24,94, 107,108,109,110 95,96,97,98	7	.002" 1% Ind.	.003" .01% Sb
25,26,27,28	10	.002" 1% Ind.	.003" .01% Sb
29,30,31,32,33,34	9	.002" 1% Ind.	.003" 1% Sb
35,36,37,38,39,40 41,42,43,44,45,46 47,48,49,50,51,52 53	7	.002" 1% Ind.	.003" 1% Sb
54,54,56,57,58,59, 60,71,62,63,64,65 66,67,68,69,70,71, 72,73,74,75,76	13	.002" 1% Ind.	.003" 1% Sb

	I_e=.5ma V_c=15V	I_e=1ma V_c=-15V		I_e=0 V_c=-10V	I_c=0 V_e=-10V	I_e=1ma I_c=5ma	I_e=1ma V_c=-10V					I_e=.5ma V_c=-20V				
TRANSISTOR NUMBER	mc	RISE TIME μ sec	α_{max} x RISE TIME μ sec	I_c ma	I_e ma	V_c VOLTS	R_{11} Ω	R_{12} Ω	R_{21} KΩ	R_{22} KΩ	α	R_{11} Ω	R_{12} Ω	R_{21} KΩ	R_{22} KΩ	α
#1	0			4.8	.023	6.1	210	80	4.8	3.2	1.4	260	60	7.6	4.4	1.7
2	2		1.4	0.2	.001	8.0	400	120	8.0	4.6	1.8	460	120	12k	6.7	1.8
3	0			0.1	.004	45	80	1[illegible]	8.0	2.8		100	20	1.5k	12k	
4	5		2.4	2.2	.001	11	210	180	16.	6.2	2.2	180	170	18	8.4	2.8
5	0		0.8	1.3	.001	45	220	110	22.	16	1.6	280	110	32	16	2.0
6	1		1.0	1.0	.012	10	260	120	4.8	1.6	2.6					
7	3		1.6	3.3	.001	7	230	140	12.	5.4	2.1	250	110	17	6.6	2.0
9	8		0.8	2.4	.002	9	440	280	17	7.8	2.6	460	280	20	9.4	2.8
10	0		0.8	1.3	.02	2.8	200	110	10	6.4	1.7	280	120	16	8	1.9
11	8		0.8	3.5	.001	9.0	280	130	9.6	6.8	1.3	250	130	14	9	1.6
13	1		1.0	1.2	.07	27.	180	60	28	12	2.5	220	80	23	10	2.4
14	2		1.4	1.5	.002	35	280	140	18	12	1.6	280	160	22	12	1.7
15	1		0.8	2.0	0.01	30	560	80	18	9.6	1.5	850	80	15	10	1.4
16	0			0.2	.002	62	120	20	1.7	16		920	30	6.9	18	0.2
17	2		0.8	2.1	.001	10	150	60	18	.2	2.3	180	60	20	9.8	2.5

20	3	0.8	0.1	0.1	[illegible]	150	90	5.8	2.2	3.2	220	80	12	4.2	2.6
21	2	1.0	3.0	.002	8.4	140	40	15	2.2	2.3	180	40	17	8	2.4
22	3	1.6	2.2	.002	15	150	60	13	5.6	2.2	200	80	17	7.2	2.5
23	open														
24	2	2.0	1.7	0.05	15.6	160	80	17	6.3	2.9	160	80	28	8.8	3.4
25	5	2.4	3.7	.001	4.2	130	100	14	6.2	2.3	280	120	20	8.4	2.6
26	9	3.	0.8	.001	23	150	220	25	10	2.8	300	260	34	11	3.2
27	short														
28	0	1.6	1.0	.003	33	250	120	32	9.2	1.4	380	170	17	9.2	1.9
29	3	0.45	0.05	.02	60	530	300	50	18	1.8	500	260	74	22	3.6
30	4	4.0	0.6	.002	11	240	260	24	9.0	0.2	140	140	17	4.6	4.3
31			0.3	0.03	60	200	20	3.4	8.6	0.6	220	40	12	12	1.3
32	2	1.6	0.7	.001	25	240	140	18	9.6	2.0	300	130	20	10	2.1
33	7		0.2	0.08	50	220	60	7.4	18	0.2	380	100	20	26	0.8
34	2	0.8	1.4	0.04	16	200	120	46	16	3.2	260	120	52	17	3.2
35	3		2.9		20	[illegible]	[illegible]	24	[illegible]	[illegible]	[illegible]	320	18	12	1.5
36	short														
37	uns.		0.1	.001	70	4.0	60	18	18		1.8k	80	3.8	8.0	0.2
38	2	3.2	[illegible]	.003	[illegible]	1.0	80	20	6.6	3.5	140	40	32	9.2	4.1

39	8		2.4	1.4	0.04	[illegible]	150	[illegible]	[illegible]	38	3.2	360	150	44	18	2.6
40				0.1	0.02	60	110	[illegible]	1.2	50	2	220	30	2.6	30	
41	open															
42	6		2.8	1.1	0.01	17	230	160	27	10	2.8	280	150	25	9.6	2.9
43	[illegible]															
44	5		1.6	1.3	.004	[illegible]	170	80	15	7.5	2.1	250	[illegible]	15	8	2.0
45	3		2.0	1.1	.002	13	150	60	14	3.4	4.4	190	50	30	6.4	5.0
46	1	1	1.2	1.5	0.05	40	180	80	34k	16k	2.3	260	80	34	16	2.3
47	4		5.0	3.1	0.01	1.4	100	60	22	5.8	4.2	120	60	23	7.2	4.7
48	osc.															
49	short															
50	2		1.6	1.6	0.04	30	280	240	50	18	2.6	230	140	18	10	1.8
51	0			0.1	.001	50	150	100	2.8	9.6		320	150	17	16	1.1
52	3		2.8	2.p	.002	14	220	130	24	9.2	2.5	220	120	31	13	3.0
53	4		0.8	0.5	.002	40	200	130	70	25	3.5	300	150	46	14	3.6
54	2		1.6	0.8	.002	42	290	160	80	28	3.0	460	200	38	16	2.6
55	6	0.50	4.8	1.6	0.01	2.5	260	220	22	14	4.4	310	220	30	6.8	5.3
56	3	0.10	4.0	1.7	.001	4.5	200	130	28	5.6	2.2	250	130	40	20	3.8
57	12	.025	4.0	1.5	.001	3.0	370	360	34	10	3.7	620	400	46	13	4.0

58	2	0.0125	2.6	2.0	.001	13	220	120	23	9.0	2.6	260	120	28	12	2.8
59	3	.050	2.6	1.7	.001	16	260	180	26	10	2.6	340	180	38	15	3.0
60	4	0.075	2.8	1.4	.001	25	350	220	24	10	2.2	480	240	35	14	2.4
61	2	010	2.0	1.6	.002	2.3	200	120	22	10	2.2	270	120	28	12	2.4
62	8	0.075	6.0	1.1	1.4	1.8	120	150	34	9.5	4.2	140	140	52	13	5.2
63	1	0.10	1.8	0.7	0.03	40	180	120	64	20	3.1	270	130	96	24	3,6
64	3	0.075	2.0	1.3	.001	18	220	130	28	10	2.8	300	140	30	10	3.0
65				0.2	.001	50	80	40	4.5	12		230	80	12	9.8	0.1
65	3	0.10	5.4	0.7	0.03	4.0	180	100	30	10	3.4	220	100	56	15	4.8
67	16	0.025	4.8	1.2	.012	7.4	260	180	25	8.2	3.3	300	180	36	10	4.6
68	5	0.075	2.8	1.0	.003	18	220	200	28	9.0	3.6	410	210	32	10	4.0
69	65	0.075	3.2	1.2	.001	25	380	320	30	12	2.8	620	360	38	12	3.3
70	2	0.075	2.0	1.6	0.01	20	600	600	42	12	3.4	900	460	38	12	3.0
71	2	0.10	2.0	1.7	.001	18	380	220	14	7.2	2.1	400	200	20	18	2.4
72	8	0.050	2.8	1.4	.002	20	360	310	16	8.4	2.1	410	300	20	9.6	2.5
73	5	0.050	2.0	1.4	.001	25	320	250	35	12	3.1	920	200	38	14	3.4
74	4	0.075	2.2	1.8	.001	20	300	180	18	9.2	2.2	340	180	21	10	2.2
75	9	0.025	4.0	1.2	0.02	12	160	180	45	15	3.4	380	200	59	17	3.8
76	4	0.10	3.2	1.0	.002	26	300	220	28	10	2.8	320	200	40	13	3.2

77	9	0.050	2.4	8.4	.002	1.5	80	60	5.2	2.2	2.4	40	80	9.8	2.8	3.4
78	3	0.010	4.8	1.4	.003	3.0	130	50	2.	7	4.6	50	40	38	7.8	5.8
79	6	0.075	2.4	5.9	.003	2.5	120	140	7.8	2.2	3.5	40	120	12	2.6	4.5
90	9	0.050	5.2	9.0	.01	1.3	40	100	6.6	1.6	3.7		100	13	2.4	5.0
81	8	0.075	3.6	6.6	.003	1.8	100	90	10	2.8	3.6	120	90	21	5.0	4.2
82	4	0.075	2.4	2.8	0.02	6.0	200	120	15	5.8	2.8	240	120	25	7.8	3.5
83	5	0.050	1.8	3.8	0.04	7.0	200	100	5.0	2.8	1.8	200	100	7.4	5.2	2.2
84	15	0.025	1,8	8	0.1	3.6	640	180	1.8	1.0	1.6	1.0k	500	3.8	1.2	2.6
85	5	0.025	1.2	2.7	0.1	13.0	300	120	5.0	4.0	1.2	400	100	5.6	3.8	1.4
86	3	0.050	3.6	1.0	0.02	14	400	120	8.6	3.2	2.6	640	120	10	4.8	2.5
87	5	0.025	2.0	3.7	0.1	6.0	220	100	9.6	4.8	2.0	240	100	12	5.8	2.3
88	3	0.050	1.2	3.5	0.1	8.0	240	60	8.4	5.0	1.6	320	60	9.4	5.2	1.8
89	1	0.075	1.2	1.4	.001	21	320	100	10	6.0	1.6	580	100	14	7.4	3.8
90	16	0.025	2.0	5.6	.002	3.5	180	320	6.6	2.6	2.4	400	380	9.4	3,4	3.0
91	15	0.025	2.2	4.3	.001	3.2	140	180	12	4.8	2.6	160	160	17	6.8	2.6
92	3	0.050	1.4	1.7	.026	25	400	230	15	9.4	1.7	440	210	12	9.8	1.5
93	10	0.025	1.8	5.6	0.02	3.4	230	180	6.2	3.0	1.9	260	180	11	4.5	2.2
94	10	0.050	2.4	3.1	.004	2.2	120	100	8.6	3/4	2.5	130	100	15	5.6	3.0

95	14	0.050	1.2	8.0	.015	2.0	140	100	6.0	2.8	2.0	160	120	8.6	4.2	2.0
96	15	0.025	1.0	4.1	.002	2.0	180	140	18	5.8	3.4	280	160	28	7.8	4.2
97	20	0.025	2.0	8.0	.003	2.0	100	160	6.0	2.4	2.4	180	160	10	4.0	2.5
98	16	0.025	2.4	7.2	.004	2.0	60	100	7.2	2.6	2.6	40	110	12	4.2	3.1
99	18	0.025	2.4	4.6	.016	3.6	150	140	7.4	3.2	2.3	180	140	10	4.6	2.8
100	20	0.025	1.4	8.6	.001	1.7	70	100	5.4	2.6	1.9	280	140	9.4	4.6	2.0
101	15	0.025	1.4	9.0	.002	1.8	180	110	4.2	2.4	1.6	140	100	4.0	2.0	1.8
102	10	0.050	1.6	4.7	.001	3.4	220	120	9.8	5.2	1.8	260	130	13.	7.0	2.0
103	20	0.025	2.8	7.0	0.06	1.5		180	9.8	2.8	3.4	120	200	16	4.2	4.0
104	8	0.050	2.0	4.5	0.02	4.0	120	120	9.6	4.2	2.2	140	110	15	6.4	2.4
105	16	0.025	4.0	5.1	.001	1.8	20	170	11.0	3.0	3.8	190	170	14	3.2	4.2
106	9	0.025	1.2	2.2	0.02	16.0	320	180	13.0	7.0	2.0	[illegible]	180	15	8.2	2.0
107	15	0.025	2.0	5.4	0.02	2.6	200	180	9.0	4.0	2.1	320	180	38	5.6	2.4
108	1	0.025	1.0	0.6	0.01	50.0	140	70	10.0	8.5	1.3	260	200	27	15	18
109	8	0.025	8.0	1.4	.001	2.2	280	200	12.0	2.2	2.0	320	220	[illegible]	2.2	8.0
110	5	0.05	1.8	4.3	.001	5.4	220	140	6.8	3.4	2.0	240	120	10	4.6	2.3

APPENDIX F

SPECIAL APPARATUS DEVELOPMENT

Gold Bonding Pulse Set: In order to facilitate the bonding and testing of experimental gold bonded transistors fabricated during the course of the contract it was necessary to modify a standard diode pulse set to provide in its testing facilities. The detailed schematic diagram of the modified equipment will be found in the following Figure.

Transistor Noise Figure Measuring Set: Because no facilities existed for the measurement of transistor noise figures and since such equipment was not commercially available it was necessary to design and build such an instrument for measuring noise figures on the transistors fabricated during the course of the contract. The equipment was designed in the form of three separate chassis for ease in servicing maximum flexibility. One chassis contains a narrow-band (10 cycle bandwidth centered on 1000 cycles) high-gain amplifier with a true power-measuring output meter. The second contains a noise-generator diode with its associated control circuitry as well as an attenuator and metering controls for introducing signals from an external source; while the third chassis contains power and bias supplies for the transistor and appropriate circuits for coupling between the other two chassis. The method adopted for measurement of noise-figures as described below is standard. As recommended in the tentative RETMA specifications, the signal generator impedance is made equal to 1000 ohms. For low noise figures, the noise diode is used as a signal source thereby taking advantage of the fact that the measurement is then independent of the noise-bandwidth of the amplifier circuits.

The noise diode does not deliver sufficient signal to directly measure noise figures greater than about 25 db. Therefore provision is made for introducing a known sine-wave signal from an external signal-generator.

In this case, the noise-bandwidth of the following amplifier must be known and the final output meter must be a true-power-measuring device. The noise bandwidth may [illegible] be calibrated by measuring a low-noise device (such as a grown-junction transistor) using in succession the diode and an external signal source. The output meter is a thermocouple device and thus measures true power provided only that the amplifier is linear. Several special provisions deserve mention. The transistor power-and-bias supply has been designed to limit the available power to about 1/4 watt in all cases in order to decrease the probability of burning out the unit under test. The output stage of the amplifier is intentionally designed to overload soon after full-scale deflection of the output meter in order to protect the thermocouple of the latter. Further protection is afforded by the voltage-limiting action of a neon-bulb connected across the primary of the output transformer. The input of the amplifier includes an attenuator to prevent overload of the first grid by the (wide band) noise signal from high-gain units undergoing test. The bandwidth of the input signal is limited by a transformer in the transistor-chassis; the transformer coupling also gives a little gain and allows transistors to be tested at high collector currents. Finally, provision is made in the noise-diode chassis (by means of a switch and pair of terminals at the back) for running the diode filament from batteries. This may occasionally be necessary because the diode filament temperature has a tendency to fluctuate at the power-line frequency thus giving about 20 mv ripple in the diode plate-current. A test point for observing the amplifier output wave form is available at the back of the amplifier chassis.

To use the equipment the transistor is inserted and the desired bias conditions set up. The noise-diode current is reduced to zero and the external signal (if used) is turned off. The amplifier input attenuator is set on "low" and the amplifier gain advanced until the meter reads a

Convenient value (less than 110 ma). If the gain is insufficient, the input attenuator may then be set on "high". The noise diode filament is then turned up until the output meter reading is increased by a factor of 1.414 (output power doubled). If the diode can deliver sufficient signal to do this, the noise figure (at 1000 cycles) is given simply by

$$F = 10 \log . 20I \text{ decibels}$$

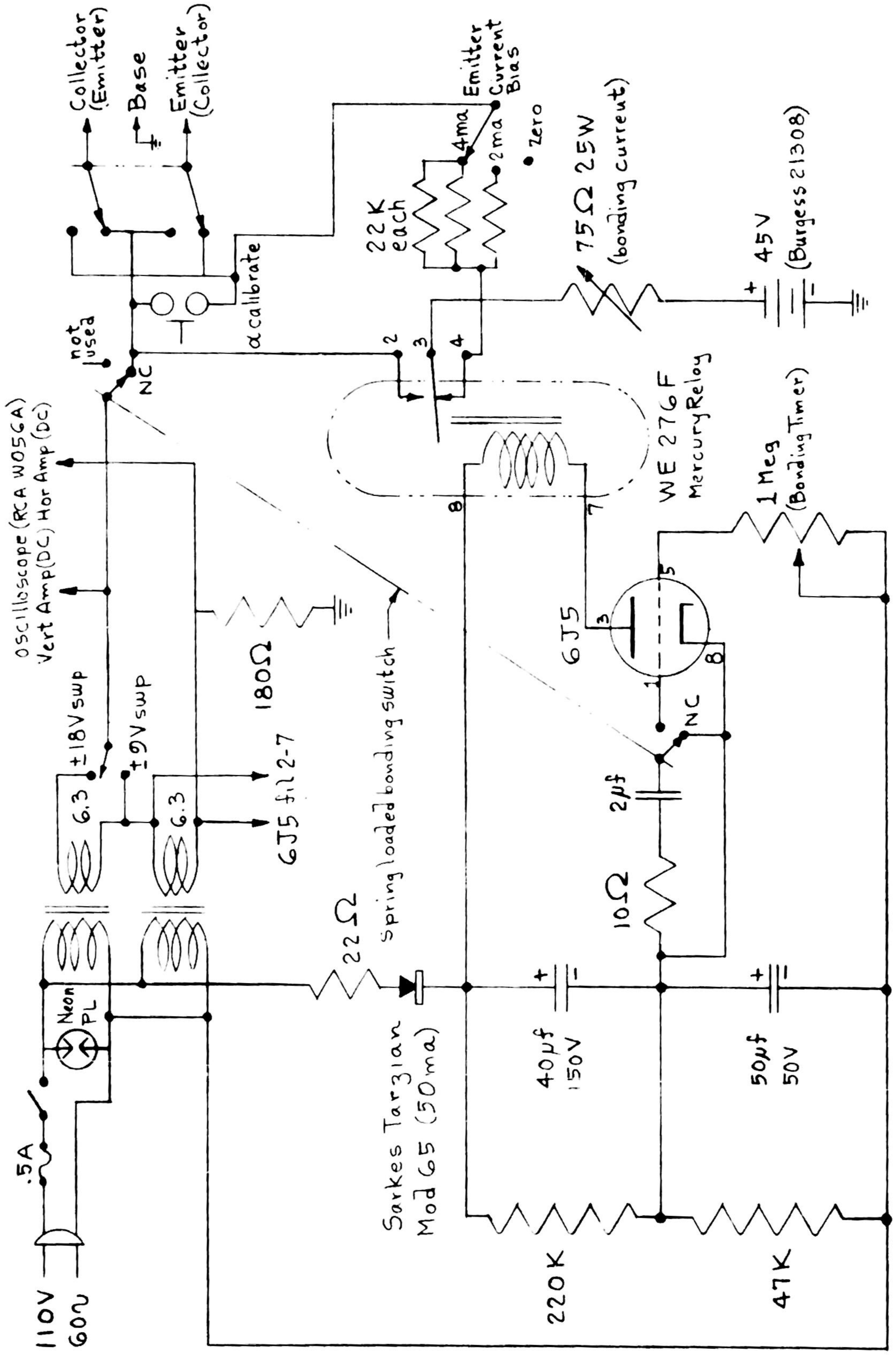
where I is the diode current in milliamperes

If the diode noise-signal is insufficient to double the output power, an external signal, tuned to the center of the pass-band of the amplifier must be used. The diode current is turned down and sufficient external signal introduced to double the output power as previously described. Under these conditions, read the voltage across the "external VM" terminals and note the position of the external-signal-attenuator switches. The noise is then:

$$F \text{ (decibels)} = 10 \log_{10} \frac{V^2}{10B} - A + 140$$

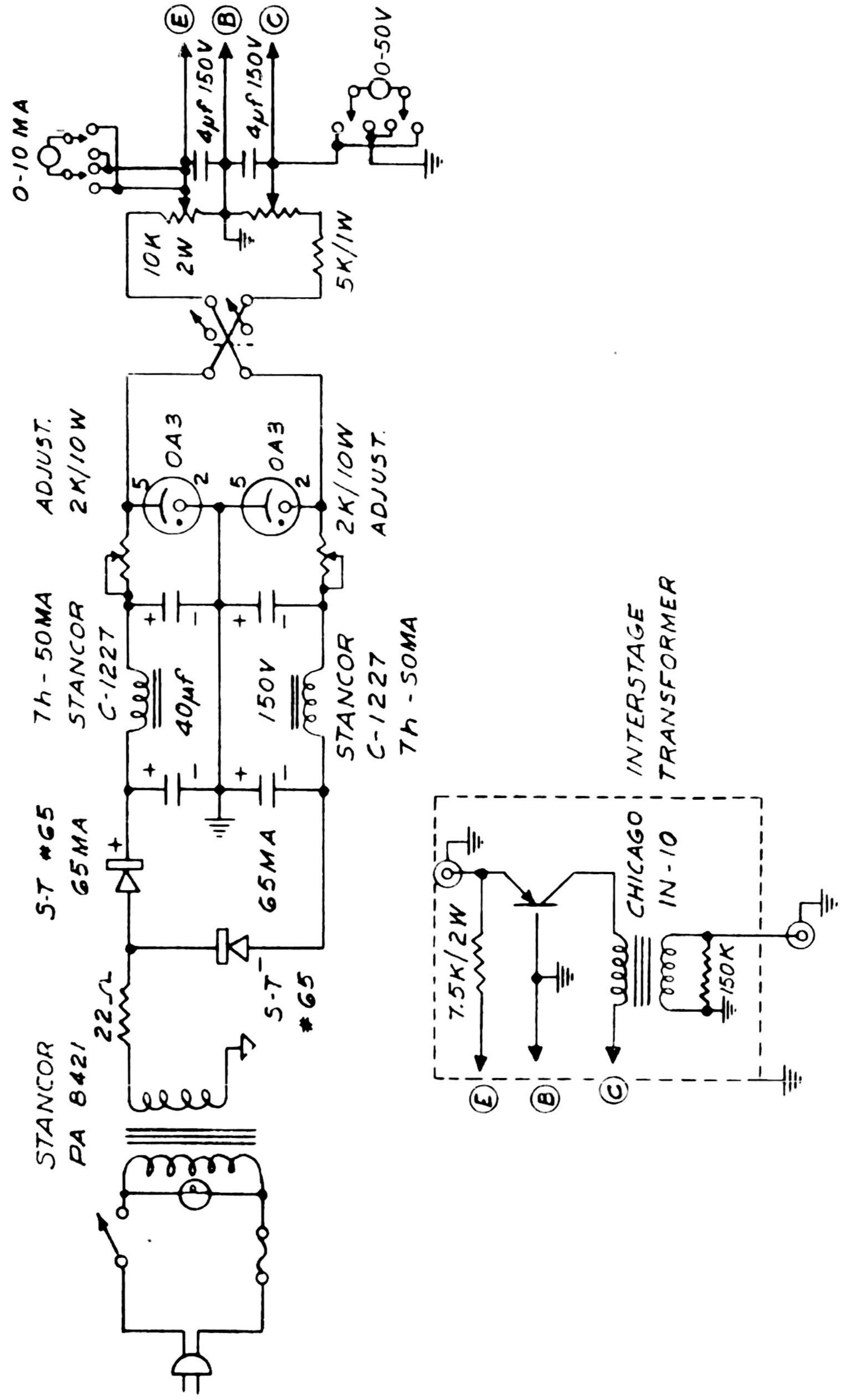
where V is the (rms) external signal in volts as measured at the "external VM" terminals, A is the attenuation read from the switches, and B is the noise bandwidth (about 10 cycles) which may be conveniently calibrated by measuring a low-noise device by both methods). Details of the noise measuring set are given in the last five of the following figures.

TRANSISTOR PRODUCTS INC.



CIRCUIT DIAGRAM FOR BONDING & TESTING SET (BONDS, MEASURES α, r_c APPROX.)

TRANSISTOR PRODUCTS INC.



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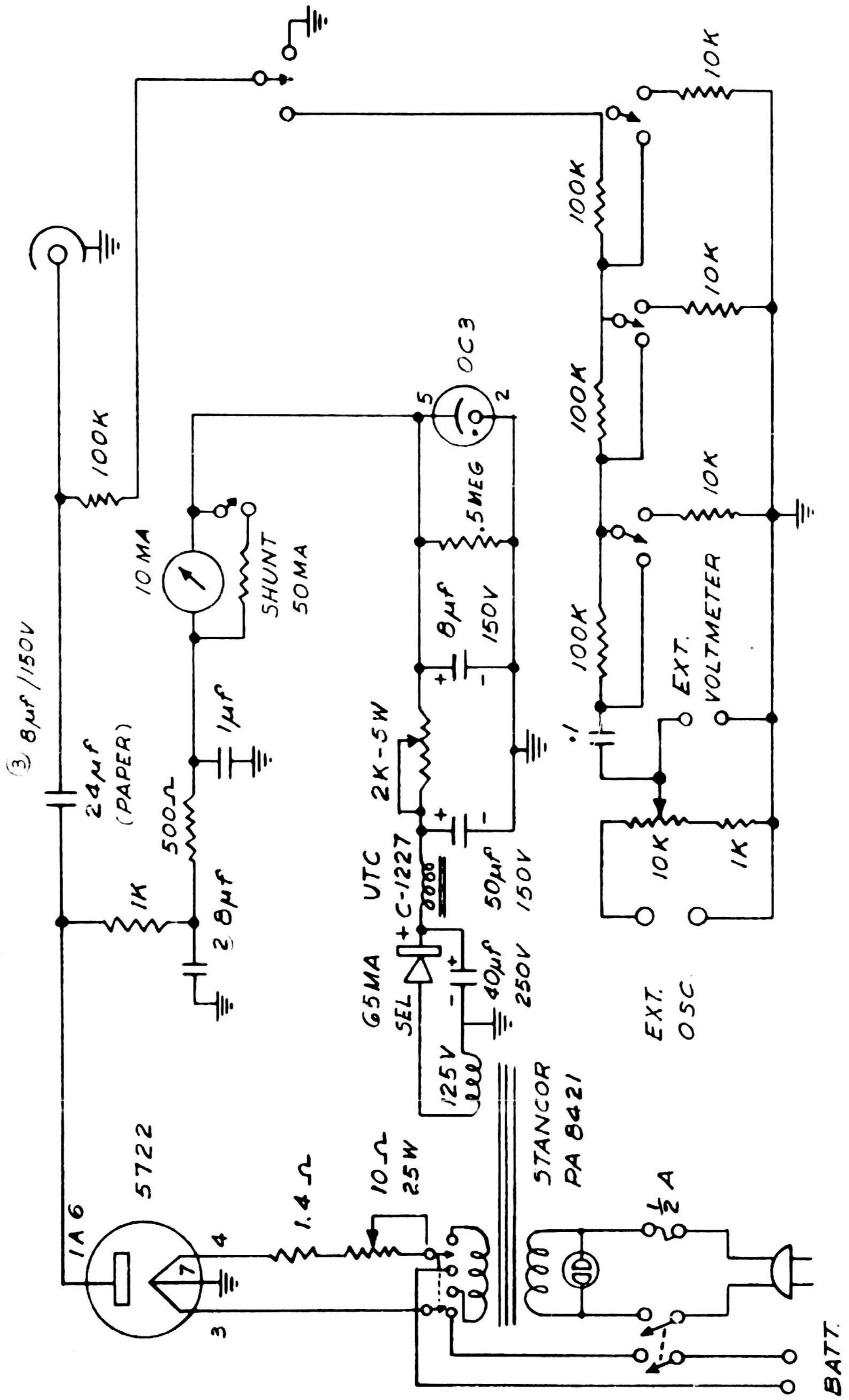

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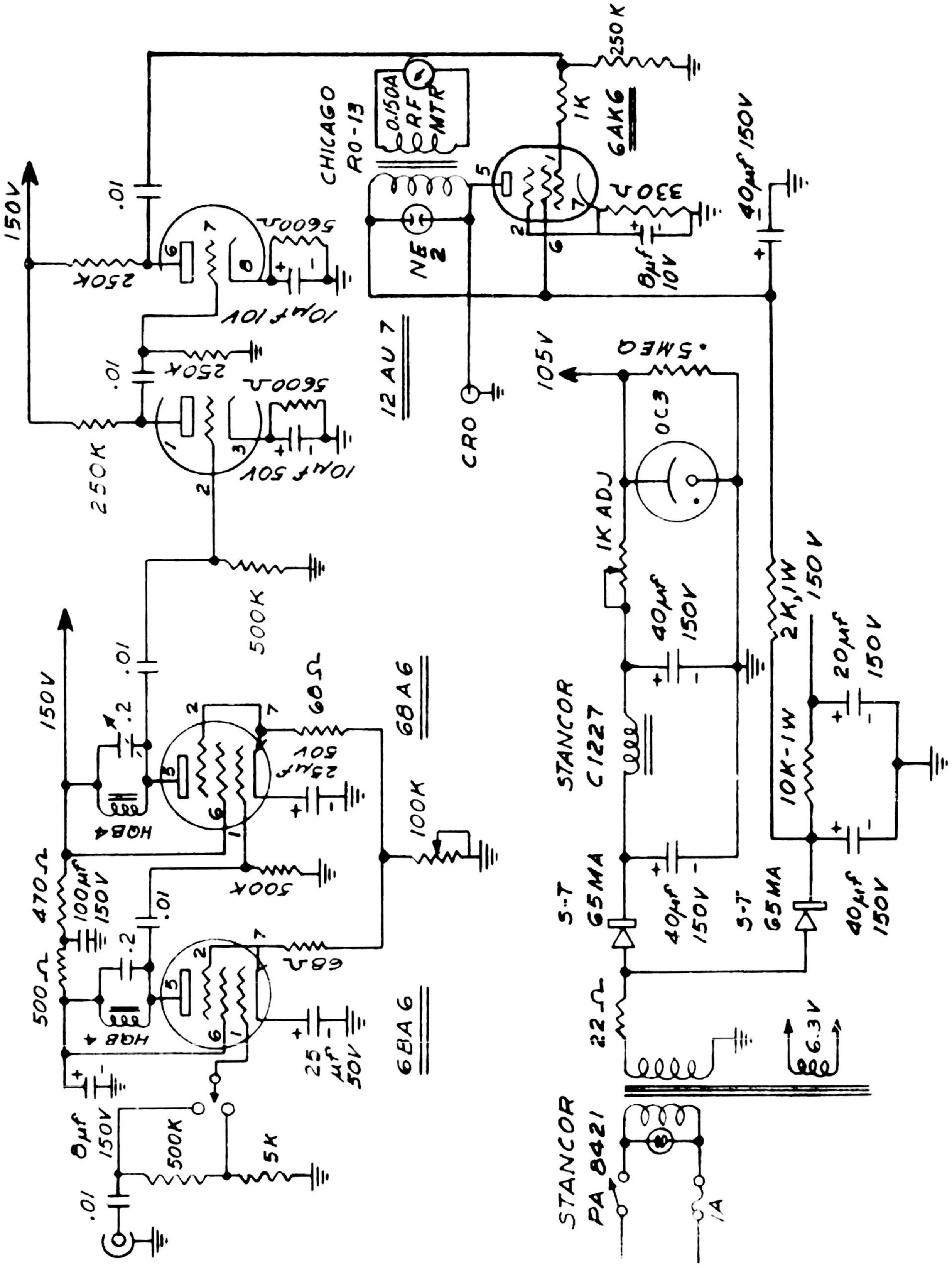

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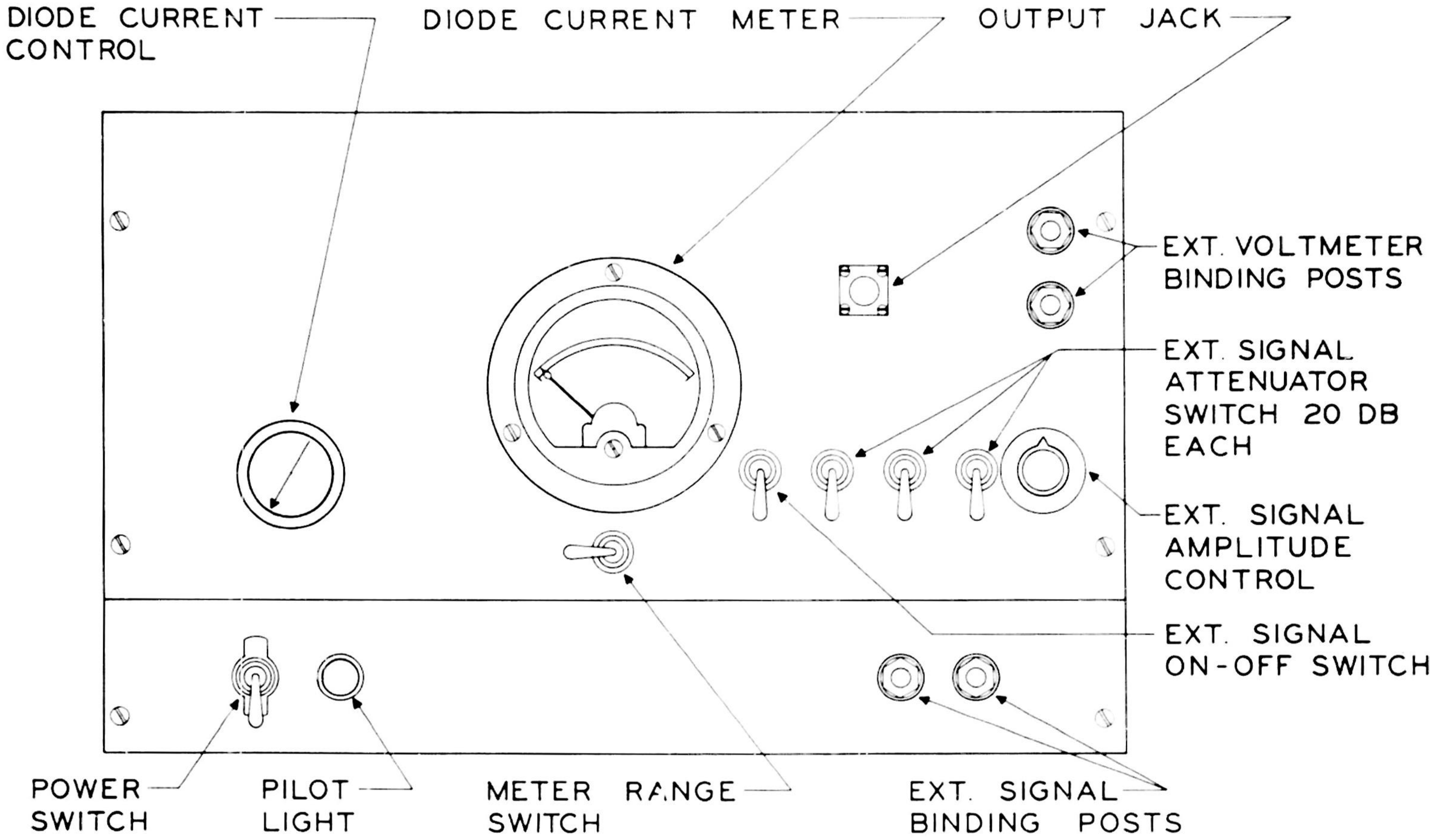
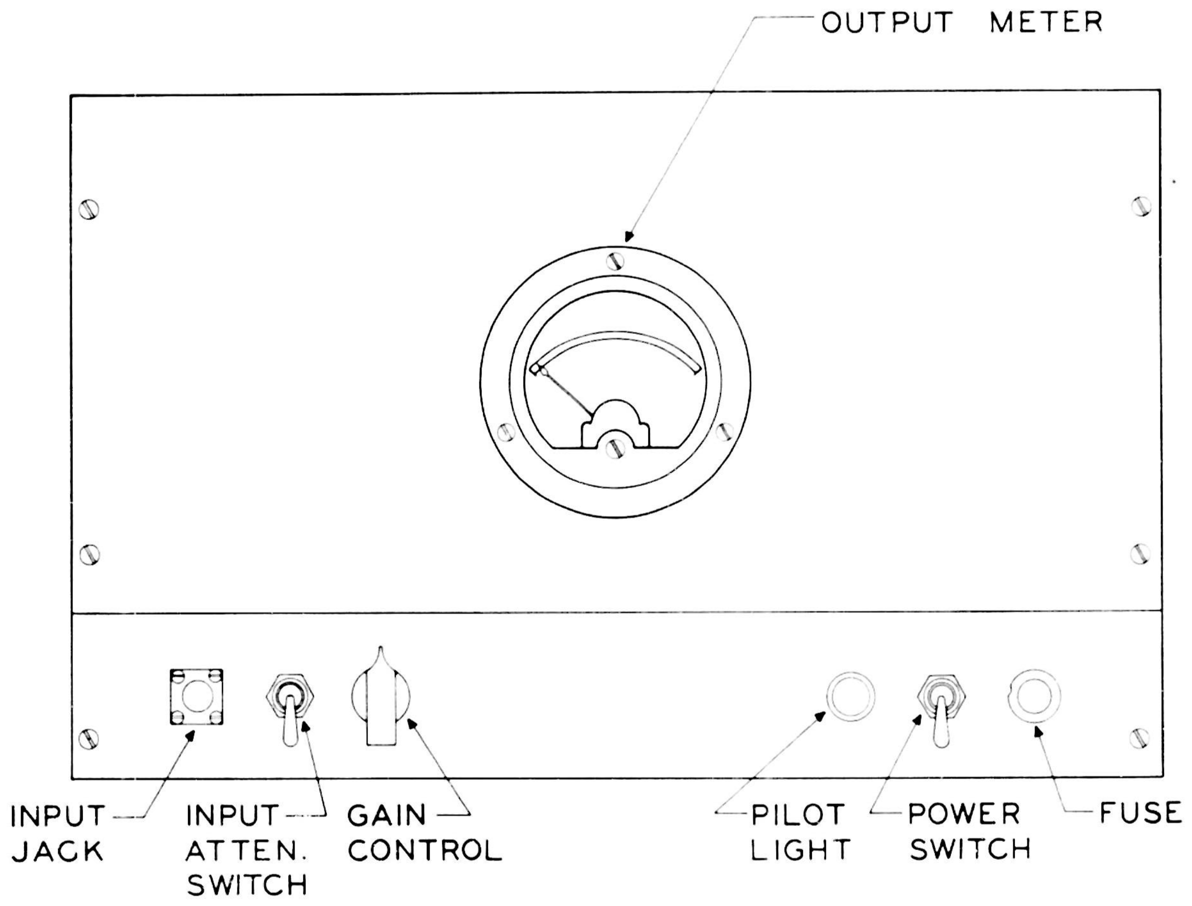


GENERATOR PANEL



AMPLIFIER PANEL