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Title PERCUSSIVE WELDING OF METAL - SEMICONDUCTOR CONTACTS

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Application of automatic production techniques to the fabrication of semiconductor devices has been somewhat limited by the requirements of conventional alloying techniques. These alloying techniques require an excessive amount of individual handling.

This thesis investigates the feasibility of applying percussive welding to the fabrication of metal-semiconductor contacts, as a solution to the problem of handling. The theory and technology of metal-semiconductor alloyed contacts, including both rectifying and ohmic contacts, is presented to determine the requirements for fabricating such contacts. These requirements were met by determining the parameters controlling the percussive welding process. The parameters were then optimized by the combination of theoretical

and empirical methods. Ohmic and rectifying contacts were fabricated by the percussive welding of gold and aluminum wires on silicon and germanium semiconductor materials.

PERCUSSIVE WELDING OF
METAL - SEMICONDUCTOR CONTACTS

by

LYLE DANIEL HECK

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INTRODUCTION

The semiconductor industry is continuously seeking improved methods in the fabrication of solid state devices. The method proposed by this thesis is a combination of two well established techniques. Percussive welding has been utilized for more than a half century, and alloying of semiconductor materials has been practiced for about a decade. As far as is known, this feasibility study is the first application of percussive welding to fabricating metal-semiconductor contacts.

The reason for the origination of this investigation was that since alloying and welding are actually the same process, perhaps some form of welding could be used to fabricate metal-semiconductor contacts. Of the different methods of welding, percussive welding appeared to be the only practical method. This is due to the requirements of dissimilar materials, and restricted heating. The desirable characteristics of percussive welding are: (1) Refractory and high conductivity materials are readily welded by the process. (2) Rapid heating, and low heat penetration require a minimum of energy (5, p. 23). (3) The welding process may be controlled for reproducible results. (4) The welds can be made quickly, and therefore, are adaptable to automatic production methods. It will be shown that the characteristics of percussive welding are compatible with the requirements of the alloy process in fabricating metal-semiconductor contacts.

METAL - SEMICONDUCTOR ALLOYED CONTACTS

The discussion of metal-semiconductor alloyed contacts will be presented in two parts. A discussion of the theory of metal-semiconductor alloyed contacts, including both rectifying and ohmic contacts, will be followed by a discussion of the technology of alloying this type of contact.

First, let a rectifying contact be defined as a contact that has the characteristic of a high impedance when the voltage bias is of one polarity, and a low impedance when the voltage bias is of the opposite polarity. An ohmic contact may then be defined as a contact that has a low impedance regardless of the voltage bias polarity.

In the case of the rectifying contact, where the metal is doped with one type of carrier and the semiconductor is doped with the other, the metal-semiconductor alloyed contact may be considered as an unsymmetrically doped p-n junction. A characteristic of alloyed junctions is that a step junction is formed (i.e., the transition region from p-type to n-type doping is abrupt). A further discussion of this characteristic will be included in the part on alloy technology.

To obtain the characteristic current equations, consider first the energy diagram of an unsymmetrically doped p-n junction shown in Figure 1 (9, p. 356). The energy band diagram in Figure 1 could represent the case of p-type metal alloyed to n-type semiconductor. Since the p-type metal is in effect very heavily doped compared to the semiconductor, the energy band diagram is unsymmetrical. The junction current is separated into four component currents: the electron current in the p region (I_{ep}), the electron current in the n region (I_{en}), the hole current in the p region (I_{hp}), and the hole current in the n region (I_{hn}). These current components may be expressed as (1, p. 272):

$$I_{ep} = \frac{Aq\, D_n\, N_p}{L_n}$$

$$I_{en} = \frac{Aq\, D_n\, N_p}{L_n}\, e^{qV_a/kT}$$

$$I_{hp} = \frac{Aq\, D_p\, P_n}{L_p}\, e^{qV_a/kT}$$

$$I_{hn} = \frac{Aq\, D_p\, P_n}{L_p}$$

where:

A = junction area.

q = charge on an electron.

N_p = equilibrium electron concentration in the p region.

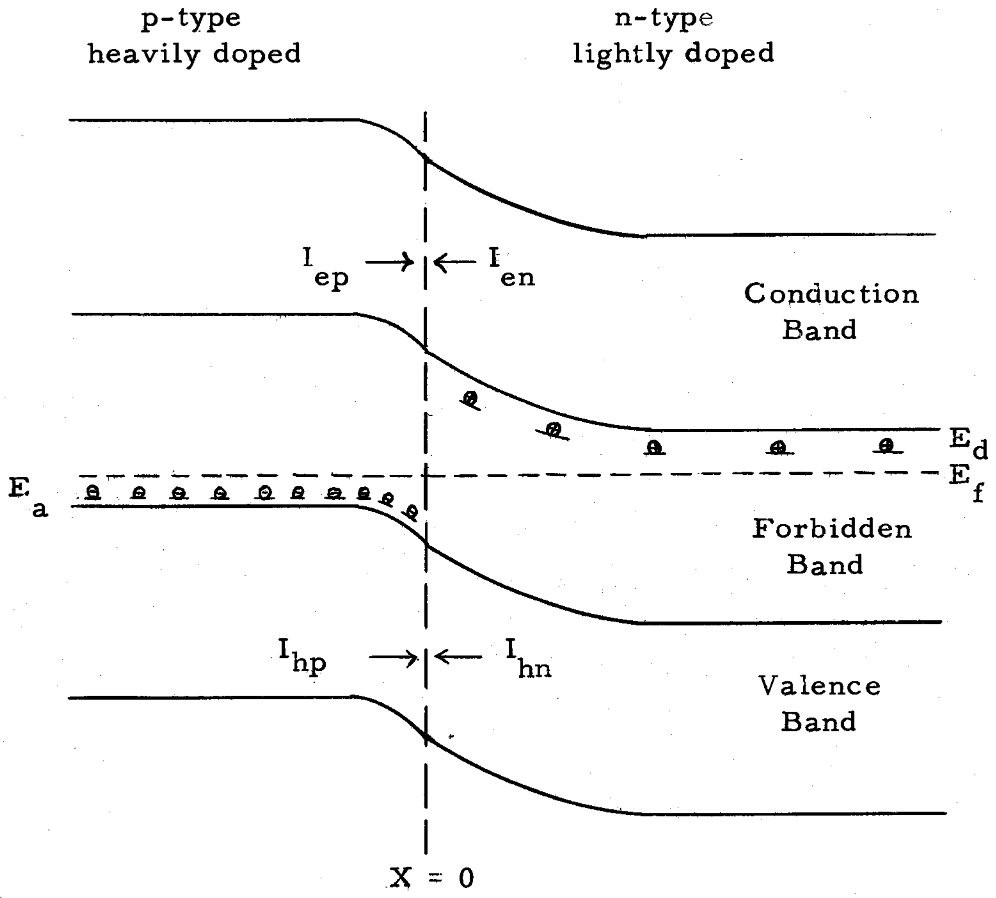


Figure 1

Energy Diagram of Unsymmetrically Doped p-n Junction

P_n = equilibrium hole concentration in the n region.

D_n = diffusion constant of electrons in the p region.

D_p = diffusion constant of holes in the n region.

L_n = diffusion length of electrons in the p region.

L_p = diffusion length of holes in the n region.

k = Boltzmann's constant.

T = absolute temperature.

V_a = applied voltage bias, positive when biased in the forward or low impedance direction.

Thus, the net electron current is:

$$I_e = I_{en} - I_{ep} = \frac{Aq\, D_n\, N_p}{L_n} \left(e^{qV_a/kT} - 1\right)$$

and the net hole current is:

$$I_h = I_{hp} - I_{hn} = \frac{Aq\, D_p\, P_n}{L_p} \left(e^{qV_a/kT} - 1\right)$$

The total junction current may then be expressed as:

$$I = I_e + I_h = Aq \left(\frac{D_n N_p}{L_n} + \frac{D_p P_n}{L_p}\right) \left(e^{qV_a/kT} - 1\right)$$

With the p-n junction biased in the reverse direction (direction of high impedance), the above expression approaches as a limit:

$$I_r = \frac{-Aq\, D_p\, P_n}{L_p}$$

since $e^{qV_a/kT} << 1$, and $P_n \gg N_p$. This current is then the reverse saturation current, and is essentially I_{hn} as previously expressed.

With the p-n junction biased in the forward direction, the expression for the current simplifies to:

$$I_f = \frac{Aq\, D_p\, P_n}{L_p}\, e^{qV_a/kT}$$

since $e^{qV_a/kT} \gg 1$, and $P_n \gg N_p$. Note that the above equation for the current in the forward direction is I_{hp}, and therefore consists of minority-carrier injection. Thus, both the forward and reverse currents are essentially hole currents. The current-voltage characteristic is shown in Figure 2.

An equivalent circuit of a rectifying metal-semiconductor alloyed contact may be drawn as shown in Figure 3.

In Figure 3, r is the body limiting resistance resulting from the bulk resistances of the metal and semiconductor materials, C is the junction capacitance, and R_b is the barrier resistance resulting from the rectifying effect. Note that the junction capacitance and the barrier resistance are dependent upon the bias voltage V_a. It

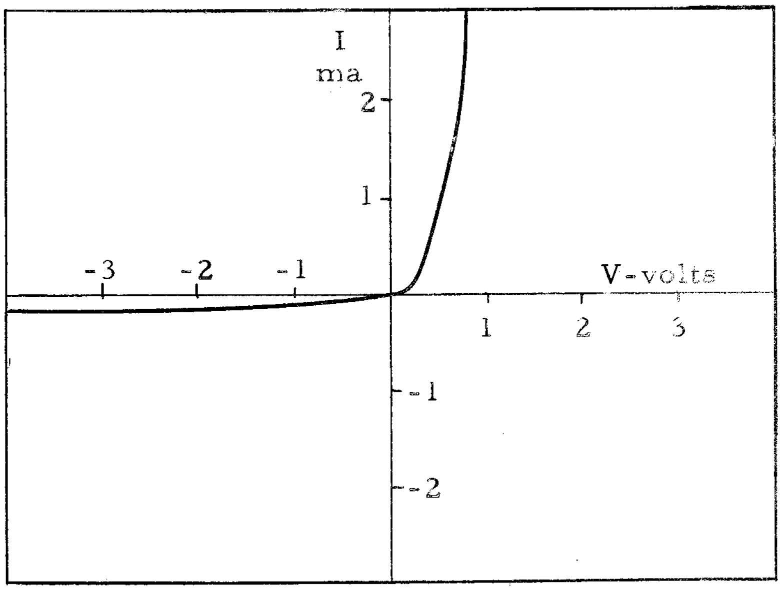


Figure 2

Voltage-Current Characteristic of Rectifying Contact

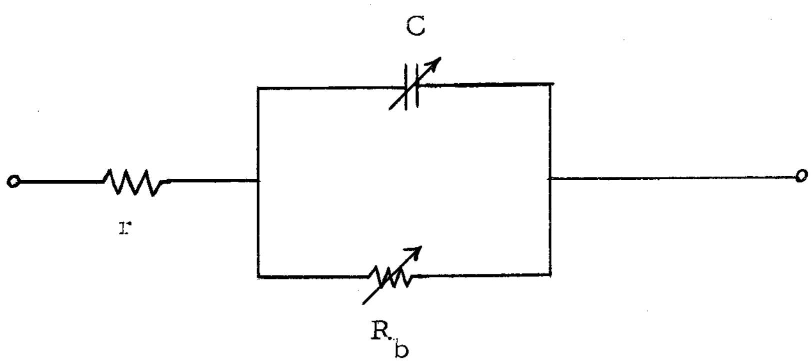


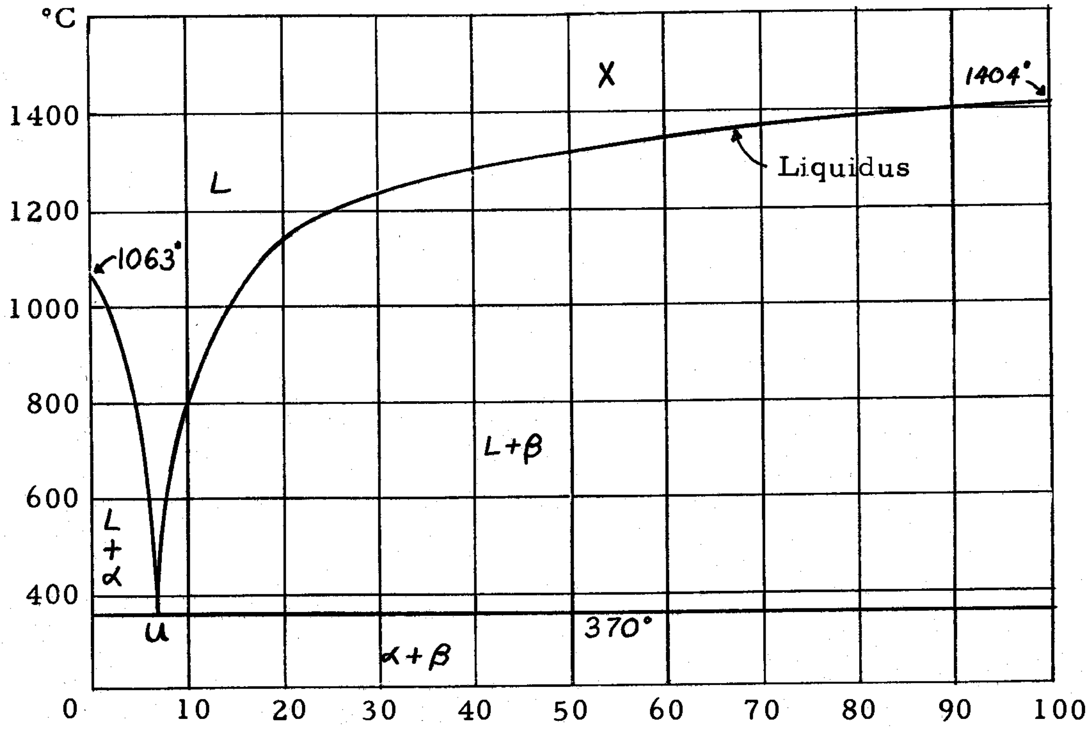
Figure 3

Rectifying Contact Equivalent Circuit

can be seen from Figure 2, that at high forward voltages, the characteristic approaches the body limiting resistance r.

Turning now to ohmic contacts, consider the case of a heavily doped metal alloyed to semiconductor material doped with a similar type of impurity. Since no p-n junction or potential barrier exists, the junction will not rectify. The resistance of the junction is comprised of the series combination of the body resistances of the metal and semiconductor materials. The high impurity concentration of the wire will tend to reduce the bulk resistance by diffusing into the semiconductor material during the alloy process, and thus create a heavily doped region. This heavily doped region will also suppress minority carrier generation, which is often important in the design of semiconductor devices.

Considerable information has been published on the technology of metal-semiconductor alloyed contacts (2, 3, 7, 11); thus, only a discussion of the pertinent processes will be included in this thesis. The alloy process is similar for both n and p-type semiconductors; hence, the process will also be similar for either rectifying or ohmic contacts. As an example of the alloying technique, consider the gold-silicon alloyed contact, with the gold doped with p-type impurities. The phase diagram for the gold-silicon system is shown in Figure 4. In the phase diagram, area L indicates the region in



Weight Percentage Silicon

Figure 4

Phase Diagram Gold-Silicon System

which both the gold and the silicon are in a liquid state, area L + α indicates the region of solid gold and liquid silicon, area L + β indicates the region of solid silicon and liquid gold, area α + β indicates the area of solid gold and solid silicon, and the point U indicates the eutectic point. In the particular alloying process to be used, the gold wire and the silicon will be quickly heated to some place in region L, as at point X. As the gold-silicon mixture cools, point X moves downward until it intersects the liquidus line. It then follows the liquidus line to the eutectic point U, segregating the silicon from the gold until the melt has the 94 Au-6 Si composition at the eutectic point. At this point, the remaining melt freezes at the eutectic temperature. It was previously mentioned that alloyed junctions had the characteristic of producing step junctions. This is due to the fact that the liquid-solid interface in the semiconductor material is well defined at all times, and that the diffusion of the p-type impurities is fairly slow. Hence, the impurity atoms do not penetrate significantly beyond the liquid-solid interface. Therefore, shortly beyond the interface, the impurity concentration will change from a highly doped p-type region to the n-type semiconductor material, producing a step p-n junction.

In the case of a rectifying contact, the junction would appear in cross section as in Figure 5. An ohmic contact would also

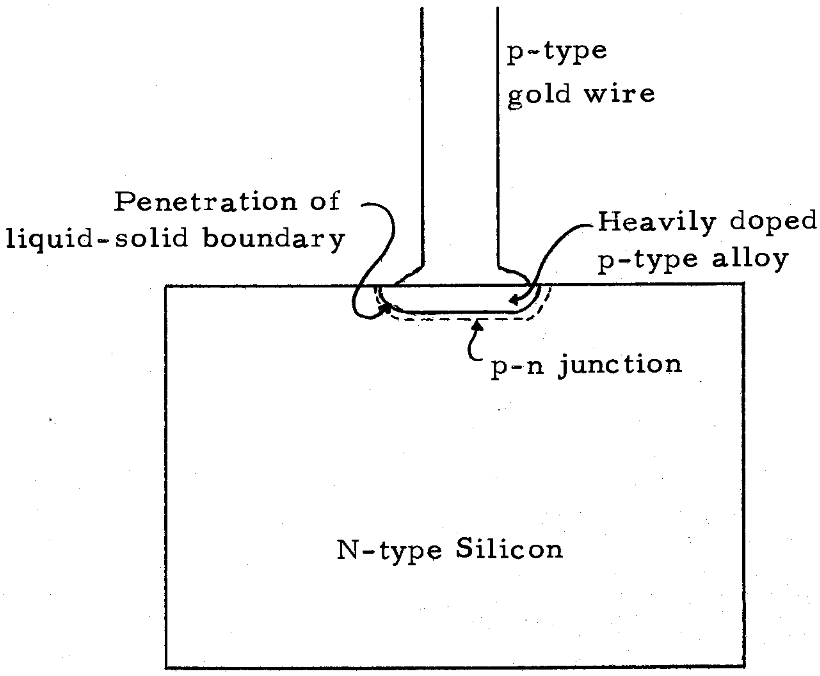


Figure 5

Cross Section of Alloyed p-n Junction

appear as in Figure 5, except that the silicon would be p-type, and thus no p-n junction would be produced.

This description of the alloying process pertains only to the method used in this investigation; it does not describe the normal alloying technique, which is similar in principle, but differs in detail.

PERCUSSIVE WELDING

Welding is the process of joining two materials by melting, fusing, and resolidifying the materials. The melting of the materials may be accomplished by either heating or compressing or both. The three main types of "heat" welding include fusion, resistance, and percussive welding (5, p. 22). Fusion welding is accomplished by using a torch or electric arc to heat the materials, usually accompanied by the addition of filler material. Resistance welding requires the two materials to be butted tightly together forming an electrical resistance at the interface. If a high current is allowed to flow, heat is generated at the interface as expressed by:

$$\text{Heat} = I^2Rt$$

where I is the current in amperes, R is the electrical resistance of the interface in ohms, and t is the time the current is flowing in seconds.

Percussive welding, utilizing a high voltage, was developed about the turn of the century (5, p. 22). Little use was made of the technique until about a decade ago when Bell Telephone Laboratories, Inc. conducted a study of percussive welding of contacts to wire spring relay blocks (10, p. 885). More recently, Western Electric has used low-voltage percussive welding in the manufacture of telephone apparatus (5, p. 22; 6). Mr. James M. Comstock of Oregon Research Engineers is currently doing research on the percussive welding of aluminum studs.

Percussive welding is similar to fusion welding in that heat is generated by an electric arc. With the two materials acting as electrodes, heating is produced by moving one electrode toward the stationary electrode until the arc is established. The arc energy is provided by the direct discharge of a capacitor. The sequence of events in percussive welding is as follows:

1. The capacitor is charged to the desired voltage (approximately 50 volts).

2. The moveable electrode is released, and is often spring driven.

3. The electrode accelerates, and an electric arc is established across about a 0.00005 inch gap in air (4, p. 63).

4. The current rises to a peak and decays approximately exponentially, melting part of both materials.

5. The arc is extinguished when the two electrodes are driven together, causing the current to rise to a second peak.

6. The two materials fuse and solidify as the current decays approximately exponentially to zero.

Much can be learned about the welding process from arc voltage and current traces as shown in Figure 6. The voltage is constant at V_0, the voltage to which the capacitor was charged, until the time of arc initiation. The voltage then drops to the arc voltage as the current rises to a peak. As energy is dissipated in the arc and the electrodes move closer together, the current and voltage decrease until the arc is extinguished. The voltage then drops to zero, and the current rises to a new peak from which it decays to zero. It is usually the case that the moving electrode is a wire, and the stationary electrode is a flat plate. Thus, during the duration of the arc, t_a, the tip of the wire is melting back, and a molten pool is formed in the plate.

The arc duration is quite important in making a good weld for the following reasons. If the arcing time t_a is too short, insufficient meltback of the wire will occur. It has been shown that the wire tip should be shaped to a feathered edge, as with a pair of diagonal cutters (6, p. 6). Hence, if the meltback is less than the length of the feathered tip, the weld will not mate the full diameter of the wire, resulting in a poor weld. At the other extreme, if the arc duration is too long, a poor weld will also result. This may be explained with the help of the energy balance expression (4, p. 65):

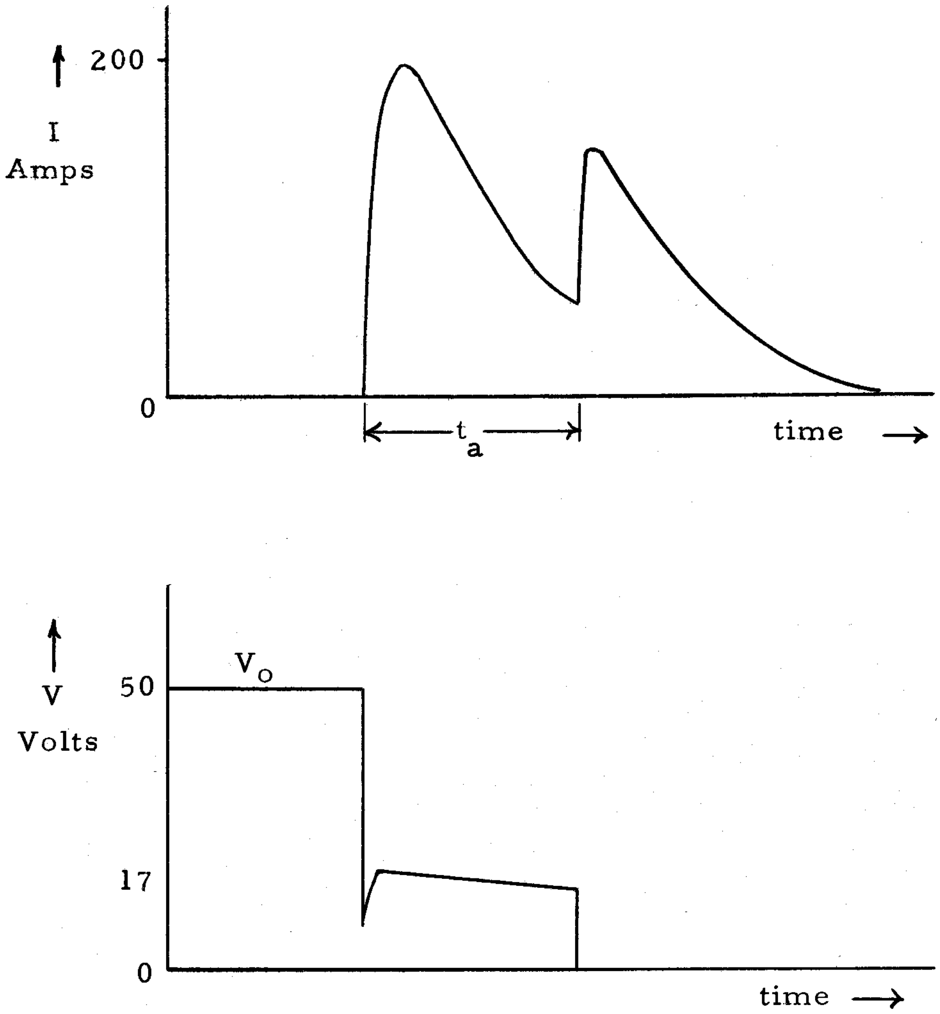


Figure 6

Arc Voltage and Current Traces

$$E_a = E_m + Q$$

where:

E_a = minimum arc energy required.

E_m = energy dissipated in melting the materials.

Q = heat conduction losses.

Thus, to keep the materials molten, the arc energy must exceed the minimum arc energy required to melt the materials (i.e., $E > E_a$). If the arc duration is too long, the arc energy will fall below the minimum arc energy required E_a, causing the materials to prematurely solidify. Thus, if the materials have completely, or even partially, solidified before contact, a very poor weld results. Coyne has found that an effective control of the percussive welding process is to monitor the arc time duration and approach speed (4, p. 55). The arc time duration is controlled by many parameters, including: approach velocity, circuit inductance and resistance, capacitance, charging voltage, and length of meltback of wire. An effective control of arc duration is to hold all parameters constant, and vary either circuit resistance or approach velocity.

Other requirements for a good weld, besides arc time duration, are arc energy, approach velocity, and material preparation.

Assuming half of the energy is dissipated in the wire, the arc energy is determined by the expression:

$$E = 2S_f (E_{mw} + Q_w)$$

where:

E_{mw} = energy dissipated in melting the wire.

Q_w = heat conduction losses in the wire.

S_f = safety factor.

The heat conduction losses may be expressed by (4, p. 62):

$$Q_w = 2\, T\, k\, A\, (t/\pi a)^{\frac{1}{2}}$$

where:

A = wire area.

k = thermal conductivity.

a = thermal diffusivity.

T = molten metal temperature.

The energy dissipated in melting the wire is:

$$E_{mw} = (T_m C_p + L)\, d\, v$$

where:

T_m = metal melting temperature.

C_p = specific heat of the metal.

L = latent heat of fussion of the metal.

d = metal density.

v = wire tip volume.

Once the arc energy is determined, the capacitance and voltage V_0 may be found from:

$$E = \tfrac{1}{2}CV_0^2$$

The approach velocity is important in producing a good weld, not only from an arc duration standpoint, but also because of the pressure needed to provide good mixing of materials upon contact. Too high an approach velocity will be detrimental by causing excess splash, bounce, or fracturing of the plate material.

Material preparation involves such factors as proper wire tip shape, surface cleanliness, and singularity of the plate electrode. As previously mentioned, the shape of the wire tip is important in controlling the variation in gap at which arc initiation occurs (6, p. 6). Surface cleanliness includes removal of oil, oxides, and other impurities from the materials. Singularity of the plate electrode means the arc must "see" only the point of desired contact. If more than one arc is established, energy is wasted and a poor weld results.

It has been noted that there is an optimum point for the parameters at which consistently good welds can be made. This point can be estimated by calculations, but must be pinpointed by empirical methods.

One of the most interesting aspects of percussive welding is the thermal behavior.

> "The very thin area of fusion is evident and examination of the grain structure of the parent metals, adjacent to the weld, indicate practically no heat affects resulting in a changed grain structure. The very narrow heat affected zone is proof that the short arc time interval is effective in preventing a significant amount of heat being conducted away from the weld zone. The particular heating effects and distribution encountered in low voltage percussion welding are advantageous in several ways. The high heat developed in the arc is ample to permit welding refractory and reactive metals. For this same reason, metals having widely different electrical and thermal conductivity may easily be joined (6, p. 14)."

Thus, it appears that percussive welding is reasonably suited to attaching wire leads to semiconductor material.

EXPERIMENTAL WELDER

A number of factors influenced the design of the welder. Some of the factors to be considered were: wire diameter, semiconductor material size and shape, low resistance contacts to the electrodes, approach velocity, elimination of bounce upon fusion of the electrode materials, facilities to hold the semiconductor material stationary, and a means to measure approach velocity. The percussive welder may be described in two parts: the mechanical structure, and the electrical circuit.

Mechanical Structure

The welder is shown in the photograph in Figure 7. The structure consists of an aluminum main frame, a spring driven aluminum armature, a stop for the armature, and a trigger for the armature. The spring from the armature is connected to the main frame by a screw, which allows the tension of the spring to be varied, and thus, controls the approach velocity. The armature stop is used because if the armature were allowed to freely drive the wire into the semiconductor material, the force of impact would shatter the semiconductor sample. Therefore, the armature stop is needed to dissipate the excess force. If the mass of the armature could be

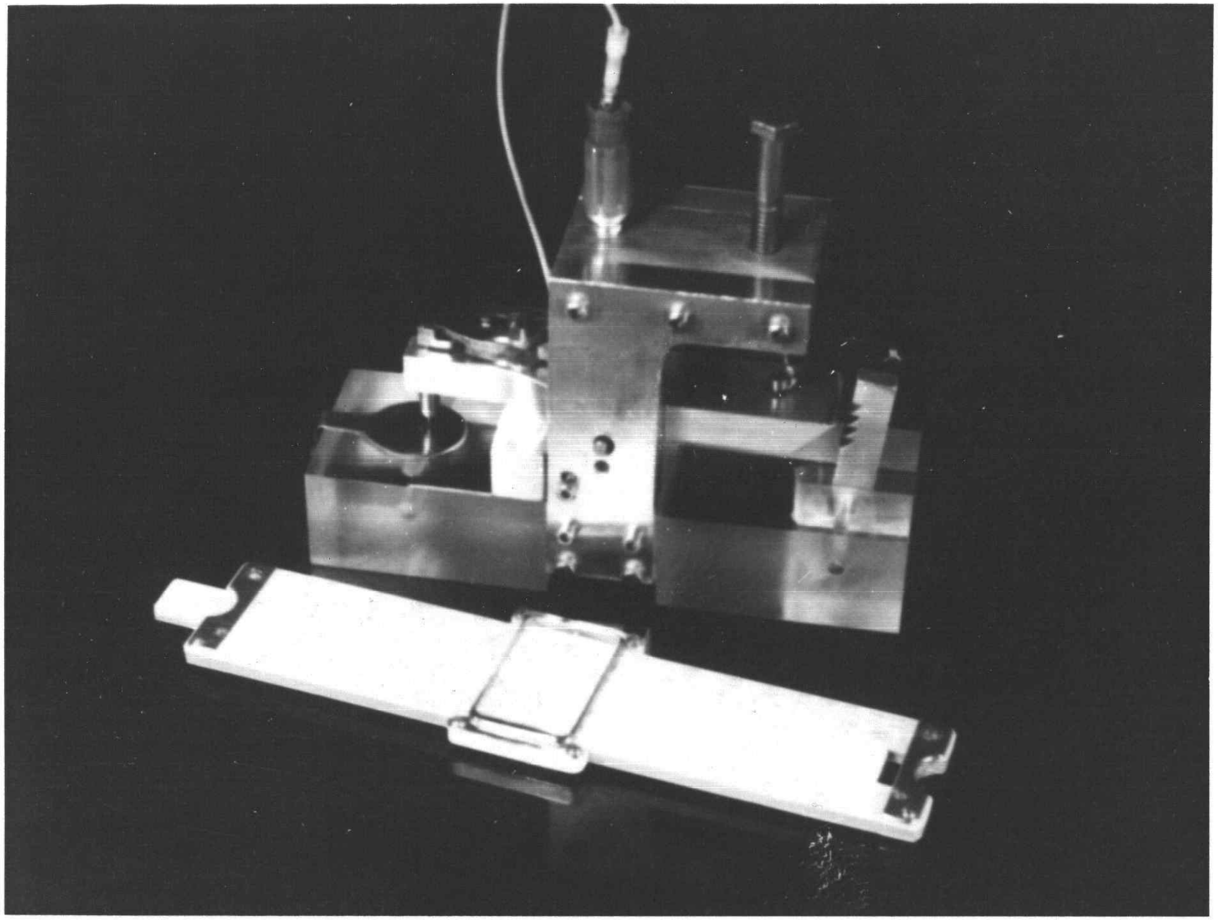


Figure 7

Experimental Percussive Welder
Shown with 6 inch sliderule.

reduced to an absolute minimum, no stop would be necessary. The tendency of the armature to bounce upon striking the stop was eliminated by coating the stop with a high vacuum grease. This grease has a high viscosity, and acts as a suction cup to the armature. The wire is fed through a capillary tube at the end of the armature, and is clamped by a copper clip which also serves as an electrical connection to the wire.

Electrical contact is made to the semiconductor material by a flat copper plate attached to the plastic frame base. The semiconductor material is held in place by a vacuum, created by a small hole extending up from the plastic base through the copper plate, and connected to a vacuum pump.

The approach velocity is measured in the following manner: as the armature moves down, an arm extending out from the side of the armature successively "breaks" and "makes" a set of contacts. Using a simple circuit, the time between "break" and "make" can be observed on an oscilloscope. If the distance traveled by the wire between "break" and "make" is determined, a measure of the approach velocity may be easily calculated.

Electrical Circuit

The percussive welder was designed for minimum resistance in all contacts. Although a small amount of resistance is desired in the circuit to control the arc duration, this resistance should be a resistor that is easily varied. Hence, the circuit resistance was minimized, and a slidewire resistor of a low value was inserted into the circuit. To achieve low circuit resistance, a number of precautionary steps were taken. Large diameter copper wires of minimum length were used for all circuit leads. The combination of the flat copper plate and the vacuum hold down system provided a fair contact with the semiconductor material. To improve this contact, it was discovered that if the bottom of the semiconductor wafer was plated with a thin layer of gold, a good contact was made to the copper plate.

The electrical circuit with lumped constants is shown in Figure 8. The value of the capacitor may be calculated from the previously mentioned equations, assuming a gold wire to silicon weld, as follows:

$$Q_w = 2\,T\,k\,A\,(t/\pi a)^{\frac{1}{2}}$$

$$= 5.4\,t^{\frac{1}{2}} \text{ joules}$$

Assume the arc duration is 200 microseconds, and the temperature is 1500°C. Then:

$$Q_w = 0.076 \text{ joules}$$

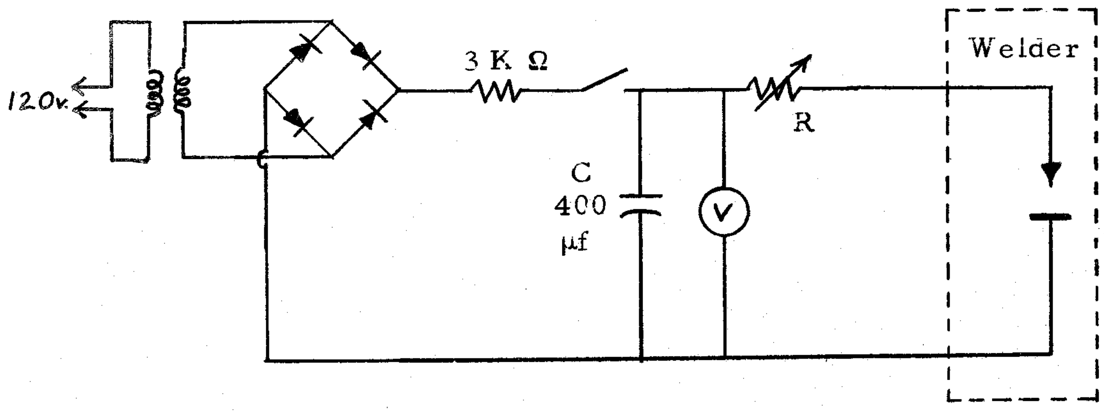


Figure 8

Percussive Welding Circuit

The energy dissipated in melting the gold wire may be expressed as:

$$E_{mw} = (T_m C_p + L)\, d\, v$$

$$= 3950\, v \text{ joules}$$

Assume the volume of the feathered tip is one half of the volume of an equivalent length of wire, and that the meltback is twice the length of the tip. Then:

$$v = 1.5\, A\, l$$

$$= 2.32 \times 10^{-5} \text{ cm}^3$$

where l is the length of the feathered tip. Then:

$$E_{mw} = 0.092 \text{ joules}$$

Since,

$$E = 2\, S_f\, (E_{mw} + Q_w)$$

and assuming the safety factor S_f equal to 2,

$$E = 0.472 \text{ joules}$$

The power supply capacitor must then supply 0.472 joules of energy.

Since,

$$E = \tfrac{1}{2} C\, V_0^2$$

and assuming the voltage across the capacitor V_0 equal to 50 volts,

$$C = 2E/V_0^2$$

$$= 378 \text{ microfarads}$$

For convenience, a capacitor of 400 microfarads was chosen, as shown in Figure 8.

The value of the variable resistance shown in the circuit was empirically determined to be optimum at a value of 0.038 ohms. This value resulted in the best current trace, and thus, the best energy distribution.

It has been suggested that power supplies containing capacitive and either resistive (10, p. 892), or inductive elements (5, p. 25) be used; thus, the energy distributions may be adjusted to overcome heat conductance losses, and sustain the arc. For this feasibility study, a power supply consisting of a single lumped capacitor has been found sufficient. A current trace of a weld joining gallium doped gold wire (0.010 inch diameter) to n-type silicon is shown in Figure 9. This curve is a close approximation to the predicted curve. The arc current rises to a peak of 184 amperes 70 microseconds after arc initiation. The arc duration is 150 microseconds, and the arc extinction peak is 142 amperes. The

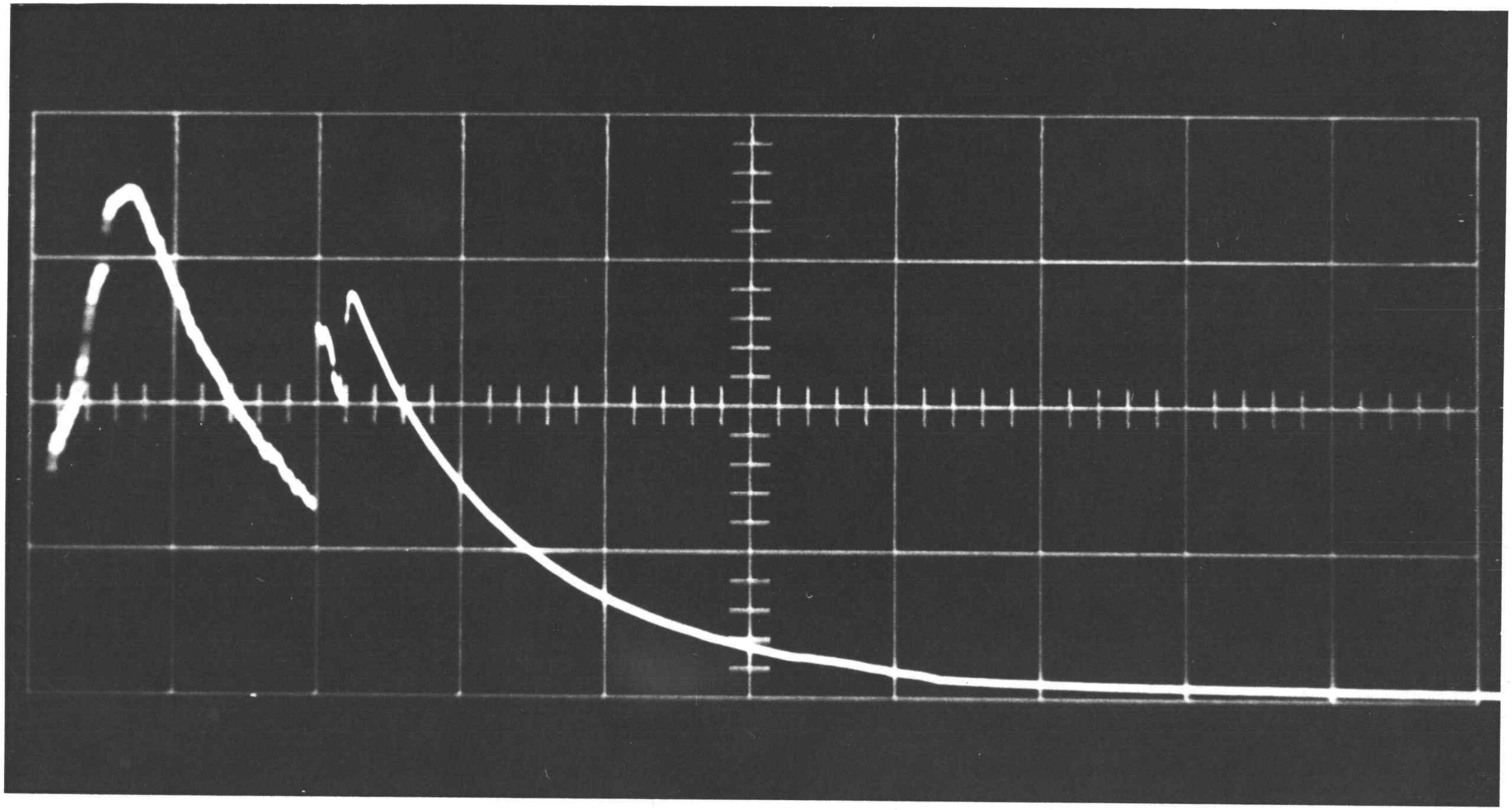


Figure 9

Arc Current Trace

Scale:
Vertical - 52.6 amperes/major division
Horizontal - 0.1 milliseconds/major division

first current peak at arc extinction is probably due to molten material bridging the arc (10, p. 890), and the second peak is probably due to the actual joining of the materials. It may be noted from the current trace in Figure 9, that the duration of the entire welding process is much less than one millisecond. This feature gives rise to the short duration of thermal unequilibrium, as previously mentioned.

EXPERIMENTAL PROCEDURE AND RESULTS

As previously mentioned, empirical methods are required to optimize the welding parameters. The reason being that all the parameters are interrelated in determining arc energy and arc time duration, the major factors affecting the percussive weld. Therefore, after calculating the capacity and charging voltage, it is much easier to determine armature velocity, circuit resistance, and circuit inductance by experimental methods.

The procedure followed in optimizing the parameters was as follows: the charging voltage (V_0) was set at 50 volts. The power supply capacitance (C) was then calculated, assuming an arc duration of 200 microseconds, the molten temperature equal to 1500°C, and a burnback of 0.024 inches, as previously shown. The armature velocity was found to be optimum at 18.6 inches/second, with an allowable variation of ±2.1 inches/second. When the velocity was too low, solidification occurred before the two materials made contact; and when the velocity was too high, contact was made before sufficient melting of the materials occurred. Notice in the low velocity weld, shown in Figure 10, the lack of melted material. A weld similar to this would also occur with optimum velocity and insufficient energy. A high velocity weld would appear normal until it was moved. The wire would then easily break away, leaving a smooth, clean crater in the semiconductor material. The circuit resistance was found to be optimum at 0.038 ohms, with an allowable variation of plus 0.102 ohms and minus 0.02 ohms. The main effect of adjusting the circuit resistance is to vary the time constant of the arc discharge current. Sufficient energy to keep the material molten until arc extinction may thus be controlled by the circuit resistance. Circuit inductance was minimized to a negligible value to reduce the number of pertinent parameters.

Thus, the controlling factors reduce to the arc energy magnitude and distribution, and the arc time duration. These factors may be observed from a current trace, as shown in Figure 9, since the voltage distribution is essentially an independent constant (4, p. 59). As previously mentioned, a weld with insufficient arc energy would appear similar to the weld in Figure 10. A weld with excess arc energy would cause excess splash, as shown in Figure 11. This type of weld had sufficient mechanical strength, but poor electrical characteristics (excess leakage in a rectifying contact).

Once the welding parameters were optimized, the preparation of the semiconductor material could be investigated. It was discovered that for best results, the surface of the semiconductor material should be lapped with #600 grit. If the surface was etched

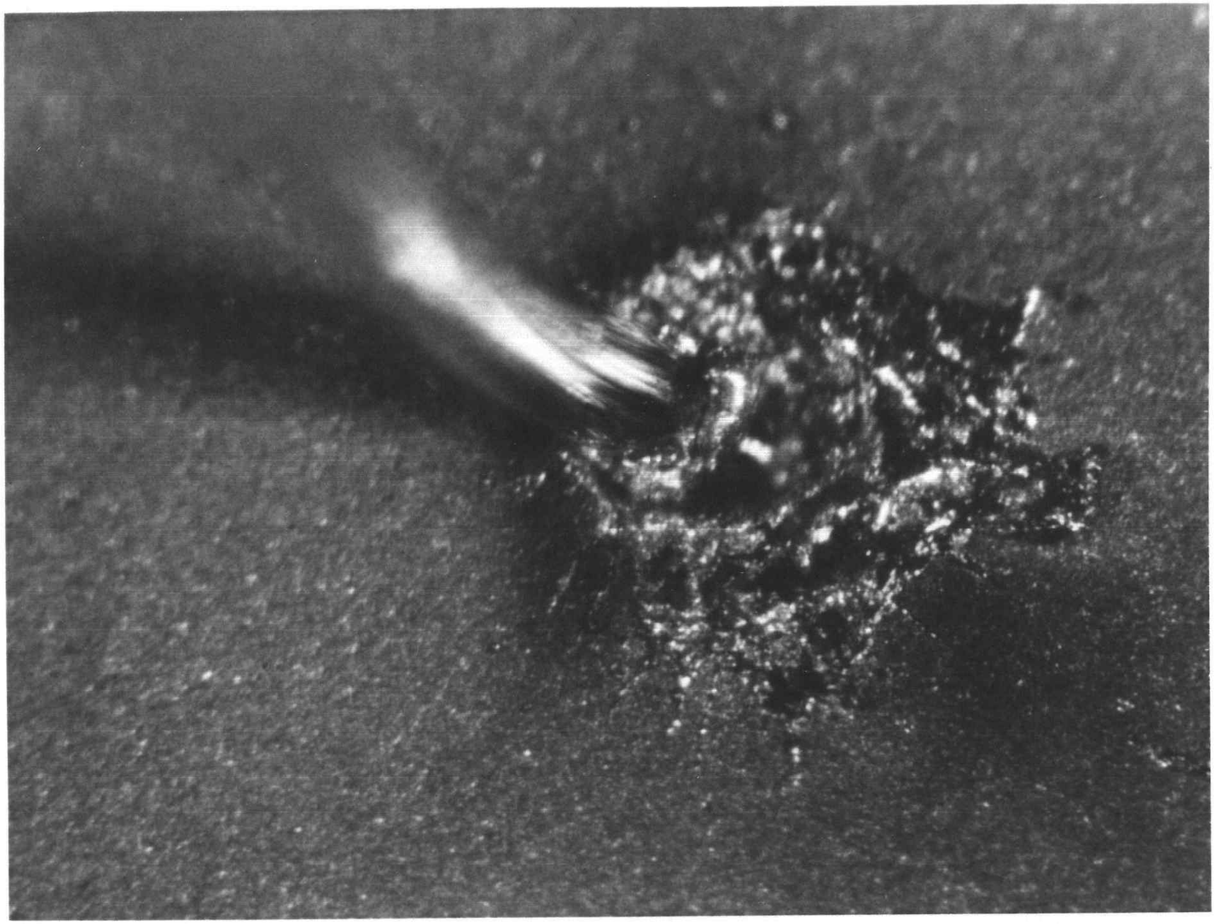


Figure 11

High Energy Weld
Magnification: X 54

to a mirror finish, the molten wire material did not wet the semiconductor surface, as is required for a good weld. It was obvious early in the course of the experimental work, that cleanliness of the semiconductor surface was quite important. This not only included immersion in boiling detergent and a rinse in distilled water, but also a bath in hydrofluoric acid. A minimum bath of 2 minutes in HF was found necessary to reduce the oxide layer to a minimum (not as important on germanium as on silicon). It was also discovered that it was necessary to complete all welding on a sample within 15 minutes of the HF bath, due to the growth of the oxide layer in air. When the oxide layer was too thick, insufficient energy was available to breakdown the layer and initiate an arc.

It was previously mentioned that to obtain a good contact between the semiconductor and the copper plate, the bottom of the semiconductor sample was coated with a thin layer of gold. The gold was applied by vacuum deposition techniques. Aluminum was also tried, but made a poorer contact than gold. The effects of plating the semiconductor top surface with gold and aluminum was also investigated. Not surprisingly, this resulted in spreading the arc, and melting the gold or aluminum, but not the semiconductor material.

Another interesting discovery was that the polarity of the power supply had a significant effect on the weld quality. The most noticeable effect of polarity occurred when materials of dissimilar majority carriers were welded (i.e., n-type wire to p-type semiconductor, or vice versa). The best welds were made in forward biased conditions, when the p-type material was used as the positive electrode, and the n-type material as the negative electrode. When reversed biased, the materials acted as a diode, resulting in an apparent high circuit resistance. This effect was also noticeable on welds between materials of like majority carriers, but of different concentrations (i.e., p^+-type wire and p-type semiconductor).

The resistivity of the semiconductor sample was another important factor in the application of percussive welding to semiconductor materials. For a good weld, there is an upper limit to the resistance of the semiconductor material. This limit is established by the fact that there is an upper limit to the circuit resistance, and that the circuit resistance includes the resistance of the semiconductor sample. Thus, with zero external circuit resistance, the upper limit to the resistance of the semiconductor sample is 0.14 ohms (0.14 ohms is the upper limit to the total circuit resistance, as previously mentioned). Resistance and resistivity are related by the expression:

$$R = r\,W/A$$

where R is resistance, r is resistivity, W is thickness, and A is area. Therefore, an upper limit may be set for rW if an effective area is determined. The effective area was found by taking a typical semiconductor sample and measuring the thickness, resistivity, and resistance. Using the above expression, the effective area can then be calculated. The upper limit found by this method is:

$$rW \leqslant 0.21 \text{ ohm-cm}^2$$

This value is valid only for the particular configuration of semiconductor sample used (circular wafers of about 2 - 3 cm in diameter, and 0.04 cm in thickness). For other configurations, a new limit must be calculated, due to the change in current density distribution.

The choice of combinations of practical materials for the wire and semiconductor is quite large. The materials investigated here were limited to a few widely used, and thus easily available, combinations. The choice was limited to gold and aluminum for the wire, and silicon and germanium for the semiconductor.

The greatest part of the experimental work was carried out using n-type silicon and gold wire. The gold wire was doped with 2.5% gallium, and was 0.010 inches in diameter. Although the materials have dissimilar majority carriers, only ohmic contacts were made. This unexplained anomaly has been noted elsewhere (8, p. 1089). The resistance of the contacts between these materials was, as was also the case of all the materials that produced ohmic contacts, undetectable. This is due to the fact that the difference between the total resistance and the semiconductor body resistance was negligible. It was noted that the total resistance was constant with either forward or reverse bias for all the ohmic contacts. This indicated that there was no rectification occurring, as is some times the case. Thus, the requirements of a good ohmic contact are fulfilled.

Photographs of a good weld, using the gallium doped gold wire and silicon, are shown in Figures 12, 13, 14, and 15. Figure 12 shows the contact just after welding. Notice the sufficient amount of melted material, but lack of splash. This same weld is shown after being etched, in Figure 13. Note the sharp distinction between the melted and the non-melted gold. Figure 14 shows the same weld after the sample was broken adjacent to the weld, and etched excessively. Notice the silicon-gold alloy material that has been etched to less than the diameter of the gold wire. This marks the limit of penetration of silicon into the gold. The small piece of gold on the bottom of the sample is from the thin deposited layer of gold. The limit of penetration of gold into the silicon is shown in Figure 15.

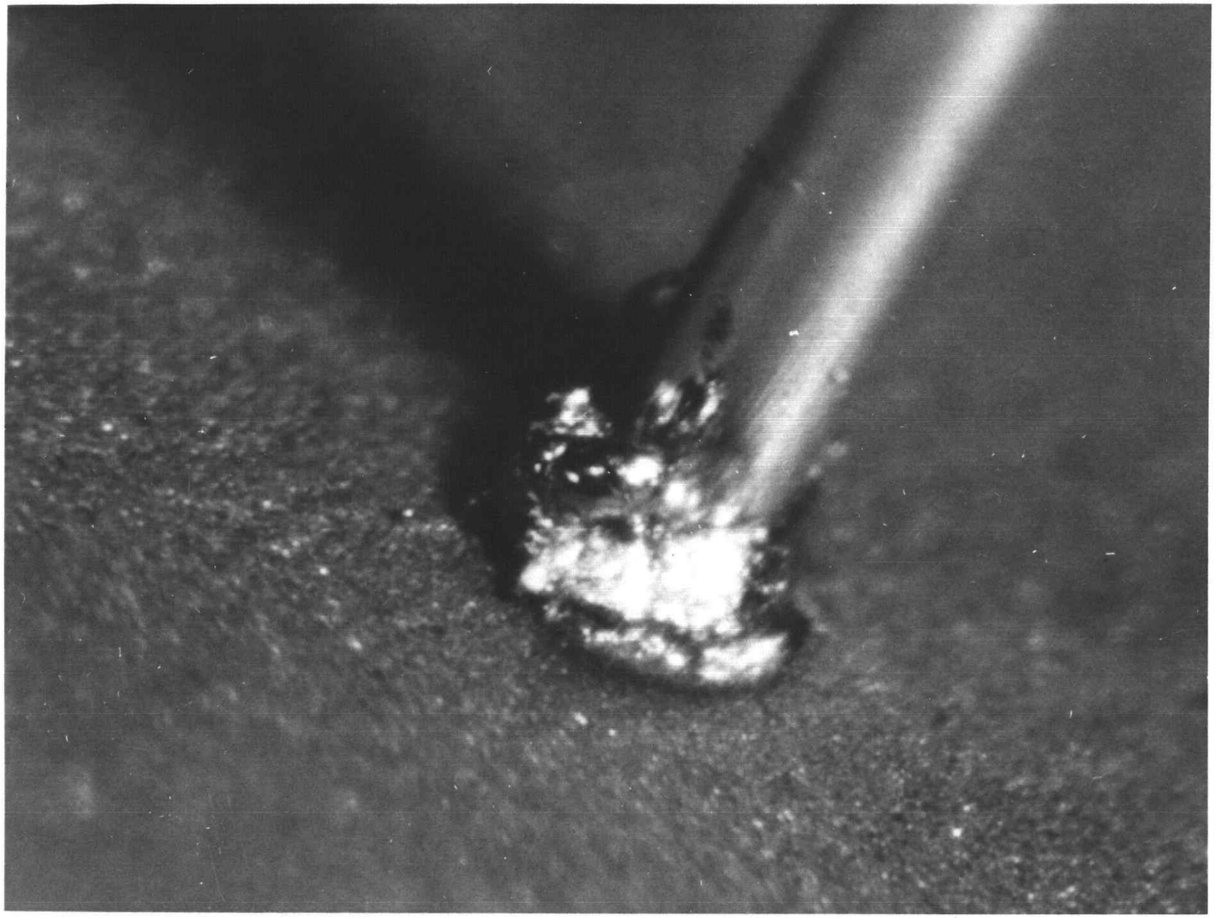


Figure 12

Gold-Silicon Contact
Magnification: X 54

Figure 13

Etched Gold-Silicon Contact
Magnification: X 54

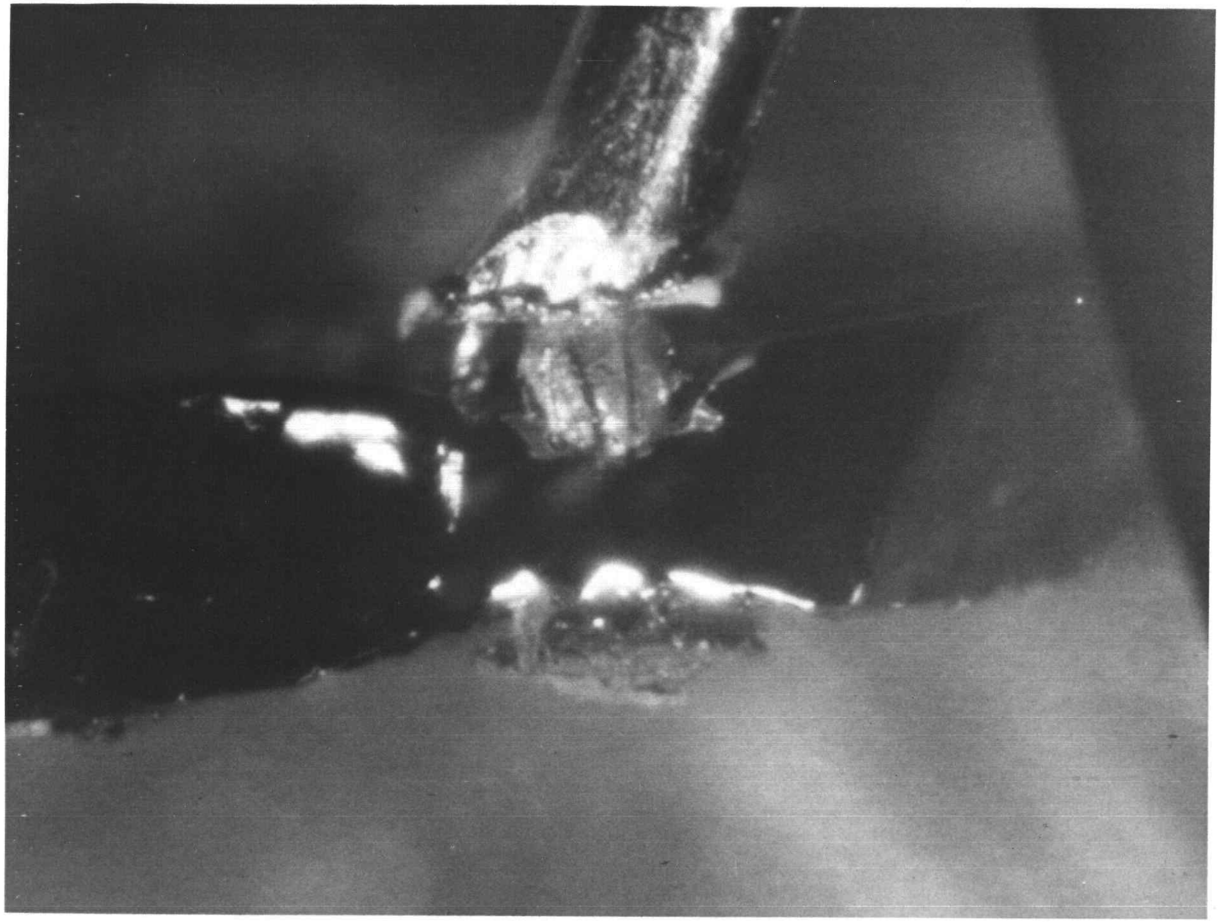


Figure 14

Side View of Etched Gold-Silicon Contact
Magnification: X 54

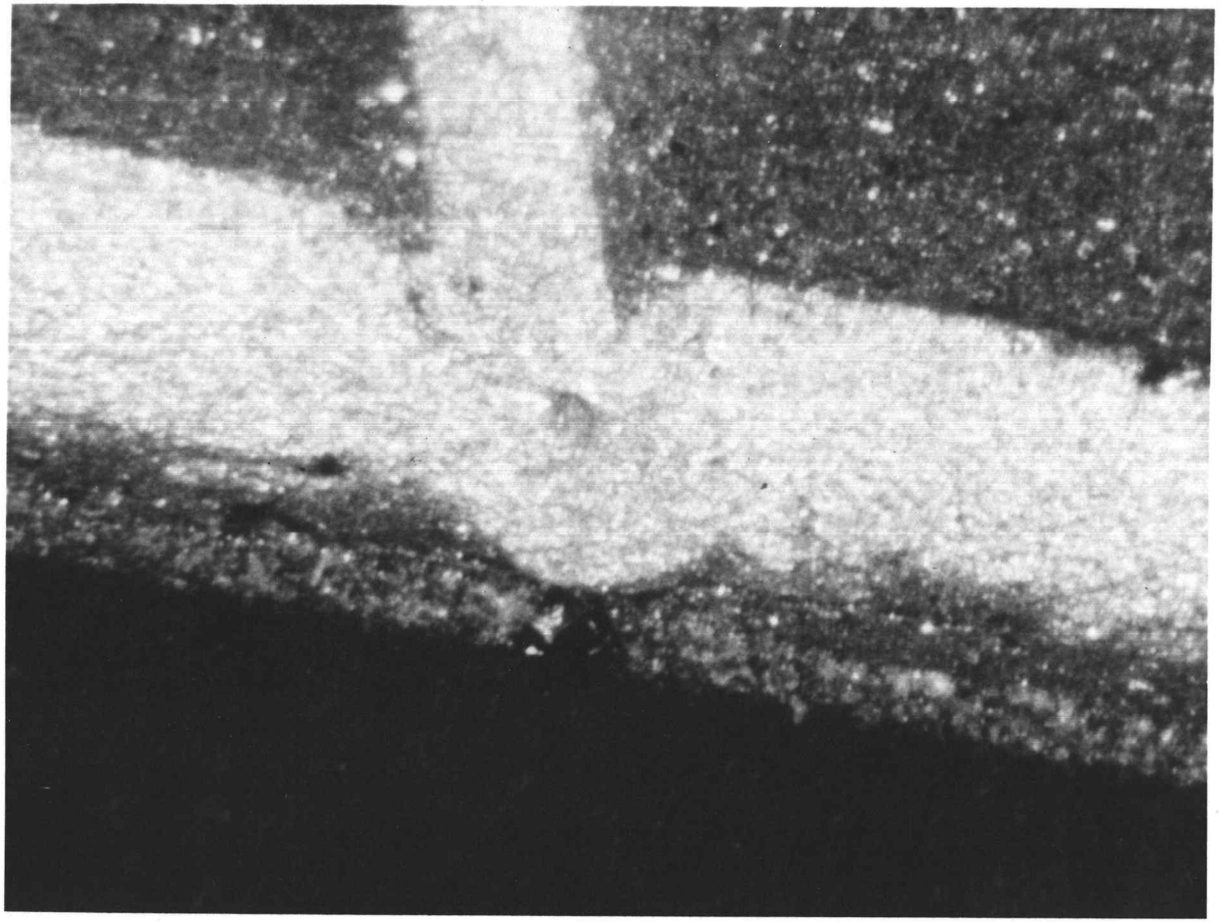


Figure 15

Cross Section of Gold-Silicon Contact
Magnification: X 54

The cross section was obtained by encasing the sample in wax, and lapping it with #600 grit.

Welds using the gallium doped gold wire and p-type silicon produced ohmic contacts quite similar to those made on n-type silicon. Welds made with 0.010 inch diameter aluminum wire and silicon had a similar outward appearance as those made with gold wire, but were found to be fairly brittle. Aluminum wire would thus be somewhat impractical for percussive welding. Welds of aluminum wire (which acts as p-type material) and p-type silicon, produced ohmic contacts similar in electrical characteristics to gold-silicon welds. Aluminum wire welded to n-type silicon produced rectifying contacts, as theory predicts. The current-voltage characteristic of such a weld is shown in Figure 16. This photograph was taken immediately after welding. Extreme difficulty in handling, due to the brittleness of the weld, prevented observation of the current-voltage characteristic of an etched sample. It is expected that etching of the sample would reduce the reverse leakage current. The characteristic shown in Figure 16 has a resistance ratio of 40:1.

Both aluminum and gold wires were welded to germanium for the purpose of fabricating tunnel diodes. The impurity concentration of the germanium was 10^{19} atoms/cm^3, and thus suitable for

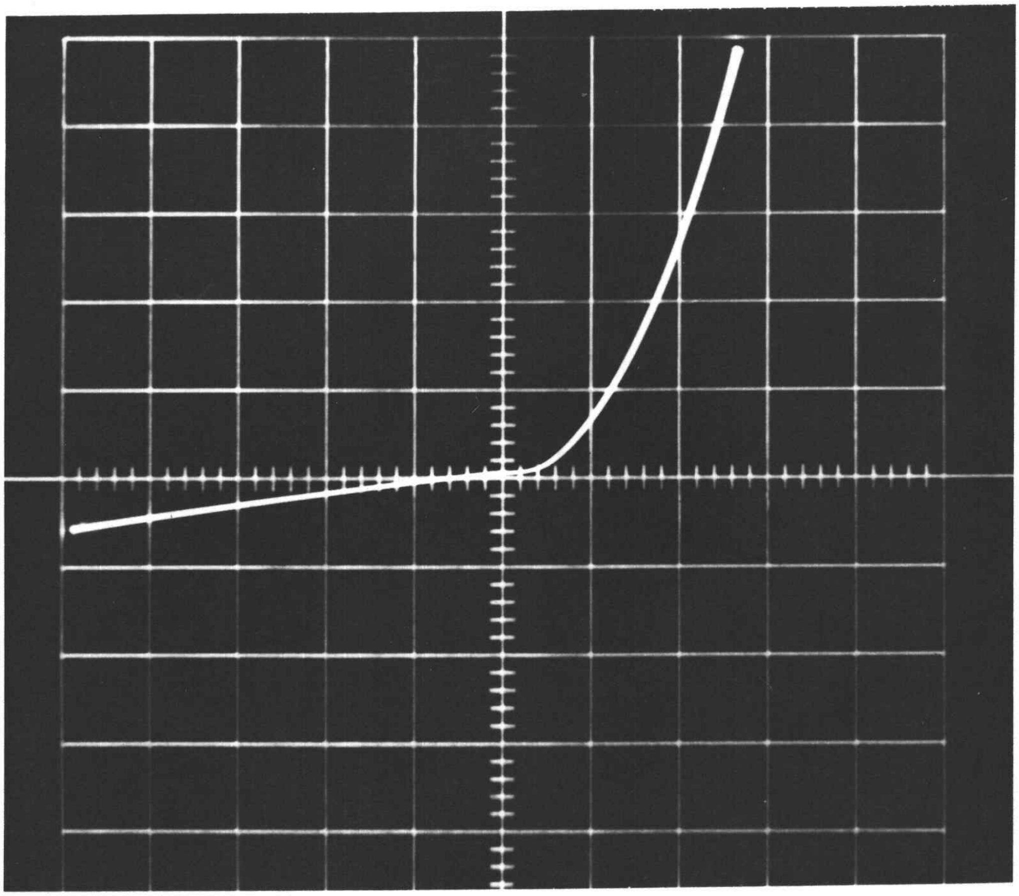


Figure 16

Voltage-Current Characteristic of Aluminum-Silicon Contact

Scale:
Vertical - 1 milliampere/major division
Horizontal - 1 volt/major division

the fabrication of tunnel diodes. It was reasoned that the short heat duration of percussive welding would eliminate diffusion, and thus create the abrupt step junction necessary for tunnel diodes. Unfortunately, both the aluminum and gold welds produced ohmic contacts. It was discovered that using these materials and normal alloying techniques, tunneling would not occur with either aluminum or gold. This indicates that some other wire material would be required in the fabrication of tunnel diodes.

It was noted that about one-quarter the energy required for welding to silicon, was necessary for welding to germanium. This is due to the lower melting point of germanium, and the lack of an oxide layer on the germanium surface. The energy required to break down the oxide layer on silicon is taken into account in the calculations by the safety factor S_f; therefore, the safety factor for germanium need not be as large as for silicon.

SUMMARY

This thesis has shown the feasibility of fabricating metal-semiconductor contacts by percussive welding. The welding parameters were optimized by theoretical and empirical methods, and were verified experimentally. Investigation was made of the basic factors affecting the application of percussive welding to semiconductor material. These factors include the surface preparation of the semiconductor material, the requirements on power supply, polarity, and the allowable resistivity of the semiconductor material. Although many combinations of practical materials were not investigated, those that were studied indicate the problems incurred in the application of percussive welding to semiconductor materials. The results of the welds were in agreement with the theoretical predictions, except for the cases of gallium doped gold to n-type silicon, and aluminum or gold to germanium. The above contacts of the gallium doped gold welded to n-type silicon remains unexplained; but it is believed that the choice of a different wire material to be used with germanium, will produce tunnel diodes. It is suggested that wire with an indium base, and either boron or germanium as the impurity, be investigated as possible tunnel diode material. The application of percussive welding to the fabrication of metal-semiconductor contacts has exhibited several important

characteristics: (1) Dissimilar materials may be alloyed with ease. (2) Arc energy is minimized due to rapid heating. (3) The low heat duration and penetration protects adjacent material from excess heat. (4) The percussive welding technique is quite fast, and therefore, is suitable for automatic production.

BIBLIOGRAPHY

1. Azároff, L. V. and J. J. Brophy. Electronic processes in materials. New York, McGraw-Hill, 1963. 462 p.

2. Biondi, F. J. (ed.) Transistor technology. Vol. III. Princeton, D. Van Nostrand, 1958. 416 p.

3. Bridgers, H. E., J. H. Scaff and J. N. Shive (eds.) Transistor technology. Vol. I. Princeton, D. Van Nostrand, 1958. 661 p.

4. Coyne, J. C. Monitoring the percussive welding process for attaching wires to terminals. Bell System Technical Journal 42:55-78. 1963.

5. Gellatly, J. S., K. F. Johnson and A. L. Quinlan. Low-voltage percussion welding. Western Electric Engineer 3:22-29. 1959.

6. Gellatly, J. S. Low-voltage percussion welding. Paper presented to the 11th Annual Joint Industrial Electronics Conference, Chicago, 1962. 42 p.

7. Goudet, G. and C. Meuleau. Semiconductors. London, Macdonald and Evans, 1957. 316 p.

8. Henkels, H. W. Germanium and silicon rectifiers. Proceedings of the Institute of Radio Engineers 46:1086-1098. 1958.

9. Shive, J. N. Semiconductor devices. Princeton, D. Van Nostrand, 1959. 487 p.

10. Sumner, E. E. Some fundamental problems in percussive welding. Bell System Technical Journal 33:885-895. 1954.

11. Van Der Ziel, Albert. Solid state physical electronics. Englewood Cliffs, Prentice-Hall, 1957. 604 p.