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PROCEDURE FOR PRESSURE CONTACT ON HIGH-POWER SEMICONDUCTOR DEVICES FREE OF THERMAL FATIGUE

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16. Abstract

A procedure for manufacturing semiconductor power devices with pure pressure contact, without solid binding, was developed in order to eliminate thermal fatigue. A silicon wafer, covered with a relatively thick metal layer, is imbedded with the aid of a soft silver foil between two identically sized hard contact discs (molybdenum or tungsten) which are rotationally symmetrical. The advantages of this concept show up particularly for large diameters. This pure pressure contact was tested successfully in many devices in a large variety of applications.

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1. Introduction /6*

High-power semiconductor components such as thyristors and diodes used to control large currents with minimal loss require a large-surface contact. This large-surface contact fulfills the further task of dissipating heat loss arising at this position. The contact must therefore assure good electrical and thermal conductivity.

Present technology employed by other manufacturers involves the depositing of the active element as an alloy to a 1 - 3 mm thick contact plate of tungsten or molybdenum. This combination is pressed together with the external connecting electrodes of copper, because of the good electrical and thermal conductivity. The alloying procedure has the advantage as a solid binding of minimal electrical and thermal transition resistance, but it demonstrates a bimetal effect in the case of temperature changes because of the differing thermal expansion coefficients of silicon and contact plate.

The aim of this research project was to develop pressure contact without the use of a solid binding in order to aviod a limitation of the maximum surface in the contact.

The maximum surface for the contact is essentially limited /7
by the diameter of silicon crystals supplied by silicon manufacturers, but not by the application requirements of high-power components, for the largest components available today must still be positioned in parallel in the circuits of large facilities to achieve the desired performance.

*Numbers in the margin indicate pagination in the foreign text.
**Work completed in May 1976.

2. Technical Demands on the System

The parameters largely influenced by the contact system such as the internal thermal resistance (stationary and transient), forward voltage drop in the areas of low and high current, destruction limit in the case of a surge current, the di/dt strength in the case of thyristors, and the load change strength must correspond substantially to the present knowledge of technology of alloyed components. It must be possible to compensate for a slightly negative effect of one or another parameter through improvements in other parameters.

A further important prerequisite is the assurance of an easily reproducible manufacturing process entailing narrow tolerances.

3. Test Procedures and their Significance /8

Tests of parameters listed under Point 2 may be divided into essentially three groups:

a) Tests conducted via a single measurement
   - stationary internal thermal resistance
   - forward voltage drop
   - surge current limit value

b) Tests requiring an extended period of time (1 - 100 hours)
   - di/dt strength (only in the case of thyristors)

c) Tests requiring very long time periods
   - load change strength

Since the load change strength depends on the individual application of the component, a standardized load condition must be simulated through time-lapse methods at higher thermal and electrical loads.

Since all these requirements must be met, it is only reasonable to examine further systems which have already passed short and medium-term tests. /9

3.1 Stationary Heat Resistance

Stationary heat resistance (R_{thJC}) is understood as the relationship of the difference of the temperatures of the barrier layer and the housing base to the power flowing from the active element through the housing base to the cooling system.

3.1.1 Transient Heat Resistance

Other values result in the case of transient heat resistance since only a portion of the adjacent contact partner is activated, depending on load duration (impulse operation). The stationary value is the limit value of the transient for longer load periods.

The stationary heat resistance is a significant experssion of quality of thermal transitions, expecially of size of surface contributing to heat transport via the contact for heat conduction.

3.2 Forward Voltage Loss and Surge Current Limit Value /10

Both values were measured as usual by a sinusoidal half-wave of 10 msec base width. A measure for the homogeneity of the current distribution along the active element is above all the forward voltage drop in the case of large currents close to the destruction limit.

3.3 di/dt Strength in the case of Thyristors

This value gives an indication of the highest current increase rate of a thyristor upon throughput without irreversible alteration of thyristor characteristics. It is measured under normal conditions; as a rule at 50 Hz frequency in the case of maximum permissible barrier layer temperature.

With the same dimensions, the di/dt strength permits a good estimation of the quality of contact in gate space, since only the immediate gate proximity is affected strongly by the temperature in the case of such a load because of the finite expansion rate.

3.4 Load Change Strength /11

The load change strength was tested in a device constructed especially for this purpose [1], in which approximately ten elements are normally tested simultaneously via heating by means of current (approximate limiting value of the mean forward current of the element) and subsequent forced liquid cooling. The duration of cycle lies in the range of a few minutes, and the temperature ranges from 30 - 110° C for the maximum permissible crystal temperature, depending on the component.

Criteria employed for evaluation are the alteration in forward voltage drop, the internal thermal resistance and the blocking characteristic.

4. Concept

4.1 Conceptual Design

Between the metallized silicon wafer and the adjacently arranged rotationally symmetrical hard contact discs of equal size, a soft metal layer must be inserted. This combination is pressed together by means of the external copper electrodes (Fig. 1).

4.2 Soft Intermediate Layer /12

Since the silicon wafer does not exhibit a completely straight and even surface as a result of manufacturing processes (sand blasting and lapping, etc.), and additionally the adjacent hard molybdenum or tungsten disc also exhibits a finite roughness and deviation from a plane surface after being subjected to a feasible amount of processing, such surfaces would theoretically only touch at three points when placed in direct contact with one another.

To compensate for this unevenness a soft ductile intermediate layer must therefore be inserted, in which the "rough peaks" of the hard contect partners may penetrate by means of plastic shaping when pressed together. This penetration continues until the carrying factor is so large that the specific pressure is smaller than the yielding point of the soft partner. Thereafter only an elastic shaping may still occur.

Because of the minimum necessary contact pressure of 130 kp/cm^2 in relation to the surface of the external connection electrodes (Fig. 2) in the case of the disc cells now used for the external connection of this element to coolers, the known "soft" metals such as lead, tin and indium as well as their alloys must be disregarded, since these cannot even withstand pressures of approximately 50 kp/cm^2 and flow away. For these application conditions only silver may be considered. /13

In practical tests a smooth foil of soft annealed silver of high purity proved to be the best solution.

Numerous trials up to emitter diameters of 50 mm at usual roughness and deviations from plane surfaces (1 - 5 μm) resulted in a minimum foil thickness of 300 μm. In the case of thinner foils the increased pressure caused the element to burst.

4.3 Contact Discs

These are understood as the intermediate plates between the silicon wafer and the external copper electrodes (Fig. 1). These plates must fulfill three requirements:

a) they must be hard, i.e. they should approximate the ideal fixed body as closely as possible in order to distribute homogeneously over the entire silicon surface pressure inhomogeneously applied externally (from the cooler);

b) they should have the same or at least a similar expansion coefficient as that of silicon, in order to prevent stress on the active element when temperature changes occur due to shifts in electrical load, and

c) they must have as good a thermal and electrical conductivity as is possible. /14

These three requirements are met essentially only by molybdenum and tungsten, but molybdenum is preferred because of cost considerations. In the case of very large diameters, the greater cost of tungsten is compensated for by the better thermal adaptability.

In addition, the contact plate must subject the soft intermediate layer to its thermal characteristic. Because of this requirement and the pressure homogeneity, the contact plates should be as thick as is feasible. Since the thermal and electrical conductivity of molybdenum or tungsten is significantly less than that of copper (factor of ~2.6) a compromise had to be found. Numerous trials resulted in an optimal thickness of 1 mm for smaller silicon diameters, while 2 - 3 mm are necessary for larger components.

The surface properties of the contact plates must include not only a maximum roughness less than the limit value of 3 - 5 μm but also a long-wave deviation from evenness less than this roughness value. If this requirement is not met, contact would only occur at a few small areas, leading to a considerable worsening of internal thermal resistance.

For protection against corrosion a thin gold or rhodium layer (distinctly less than the roughness) is deposited on the contact plate. The alloying by means of diffusion occurring under operating conditions of temperature and pressure is not disadvantageous, since in this manner the expansion characteristic of the silver foil is determined by the expansion of the molybdenum disc. /15

The two contact discs on both sides of the silicon must be of identical size and arranged rotationally symmetrical, since pressure increases may otherwise occur where material projects beyond an edge and may lead to the destruction of the silicon element.

4.4 Connecting Electrodes

A connecting electrode is understood as the contact piece normally manufactured from copper forming the external limits of the component. They are in direct contact with the cooling system and must compensate for pressure inhomogeneity stemming from the cooling system. For this reason the thickness should be made as great as possible. If the thickness is as large as the diameter, even a pressure applied at a single point from the cooling side is homogeneously distributed over the molybdenum disc (Principle of de Saint Venant). Precondition is that the shaping remains within the elasticity range. When operating the component a temperature difference /16 between the internal and the external side occurs due to the heat flow in copper. This temperature difference leads to a differing enlargement of the two current surfaces of a connecting electrode, causing it to bulge. This bulge is compensated up to a defined temperature difference by the external pressure. At higher temperature differences the edges of the copper pressure piece expand away from the molybdenum disc, on the one hand, and the center of the copper pressure piece expands away from the cooler, on the other hand, accompanied by an increase in heat resistance, which in turn accelerates the process.

According to theoretical considerations [2] , the permissible conductivity rate per connecting electrode without the above-mentioned bulging is proportional to the quantity d^4/h^3 (d = diameter of connecting electrode, h = thickness).

The proportionality factor is a quantity dependent on pressure and the material constants of the contact material (normally copper).

This result is not in agreement with the demands of the principle of de Saint Venant. The disc cell housing available on the market today represents a useful compromise between the two requirements. The same requirements apply to the composition of the surface and the contact discs. The inside diameter of the connecting electrodes must be adapted to the hardness of copper. In the case of soft types of copper (on the Vickers scale $\geq$ 20 kp/mm^2) the diameter must be somewhat smaller than that of the molybdenum disc, while in the case of hard copper types (on the Vickers scale > 40 kp/mm^2) the copper surface must be "extended". /17

4.5 Housing Forms

In practice essentially two systems are employed for creating pressure contacts (Fig. 3):

a) one system in which the necessary pressure is applied in the system itself, e.g. via Belleville springs, and for reasons of construction one connecting surface is smaller (flat bottom or screw cell);

b) one system in which the pressure is applied externally, i.e. by the cooler, and in which both connecting surfaces are of the same size (disc cell).

In system b), optimal electrical and thermal values are achieved when the surfaces of the contact partners are even.

In system a) the relationships are substantially more complicated. Because of the pressure applied internally and the pressure supports at the soldering points of the flange of the housing top, the housing bottom arches (when observing the inside surface of the base plate, it is then concave by an amount of 13 - 20 µm in the case of normal pressures when disc diameter is 23.5 mm). For pressing the entire surface of the active part on the housing bottom a recess of equal size is therefore previously made on the inner side of the base element by means of plastic shaping in a pressure tool. /18

4.6 Metallization on Silicon /19

Since there are no production techniques entailing reasonable levels of cost and work for manufacturing plane surfaces with a roughness of less than 3 - 5 µ, the metallization on the silicon element must assume a certain thickness to ensure cross conductivity. In the case of very thin layer thicknesses the cross conductivity may be disregarded, so that only those points in direct contact contribute to current and heat transport. This is expressed in a low destruction level in the case of surge current and lessened di/dt strength in the case of thyristors. Fig. 6 is a representation of the failure rate in surge current of components manufactured in current series, first with a thin metallization layer (two nickel layers deposited without electric current and atomic gold layer as for a soldered contact), then 3 µm and 10 µm of tungsten, respectively. It can be clearly seen that in the case of thick metallization layers the failures do not begin until substantially higher values are achieved (12.5 kA as compared to 9 kA).

Employing tungsten may not only improve the cross conductivity but also increase the breaking strength approximately by a factor of three. Especially in the case of thin elements this is a substantial advantage. The disadvantage involved is the very complicated technique of carrying out depositing from the gaseous state.

As a further possibility for achieving high cross conductivity /20
thick (3 µm) gold layers were examined (galvanic strengthening of original atomic gold layer). This system does not exhibit load change strength due to diffusion alloying with the silver foil under application of temperature and pressure. For this reason it is necessary to insert an intermediate layer to prevent this effect. Through numerous trials it was proven that an approximately 0.4 µm intermediate layer of rhodium is the most advantageous. A sufficient cross conductivity may also be endured by means of depositing a thick aluminium layer (15 - 20 µm). For prevention of

oxidation an approximately 1 m silver layer must simultaneously be deposited and both layers sintered between 400 and 500° C. In this case the soft silver foil must be excluded, since otherwise alloying with the aluminum layer occurs. This system has the additional advantage that the number of necessary junctions is reduced by two.

5. Application of the Procedure /21

The direct pressure contact without solid binding using copper electrodes and thick gold contact layer has found applications at BBC since 1973 for all power diodes and thyristors and has proven successful in practical applications.

Exceptionally good results were achieved in all hard reliability tests and equivalence to the alloyed and soldered contact system was proven.

- In the load change test more than 500,000 load changes without alterations in parameter were achieved.
- In the di/dt test with di/dt values of $\geq$ 500 A/µsec at 50 Hz frequency, stability over more than 1000 hours was achieved.
- The surge current and heat resistances, with respect to various components, achieve nearly the theoretically possible values as in the case of the alloyed systems.
- The advantage of this system will be seen more clearly in the case of still larger contact diameters - diameters of 75 mm are now being discussed. In the case of elements having on the anode and cathode isde p- and n-structures each, as in the case of backwards conducting thyristors or power triacs, the direct pressure contact is the ideal contact method. An alloyed contact of a p- and n-doped structure is only made possible with technological processes and reduction of parameter. The advantage of complete pretesting is already being utilized, so that all contact metal parts may be re-used in the case of rejects. /22

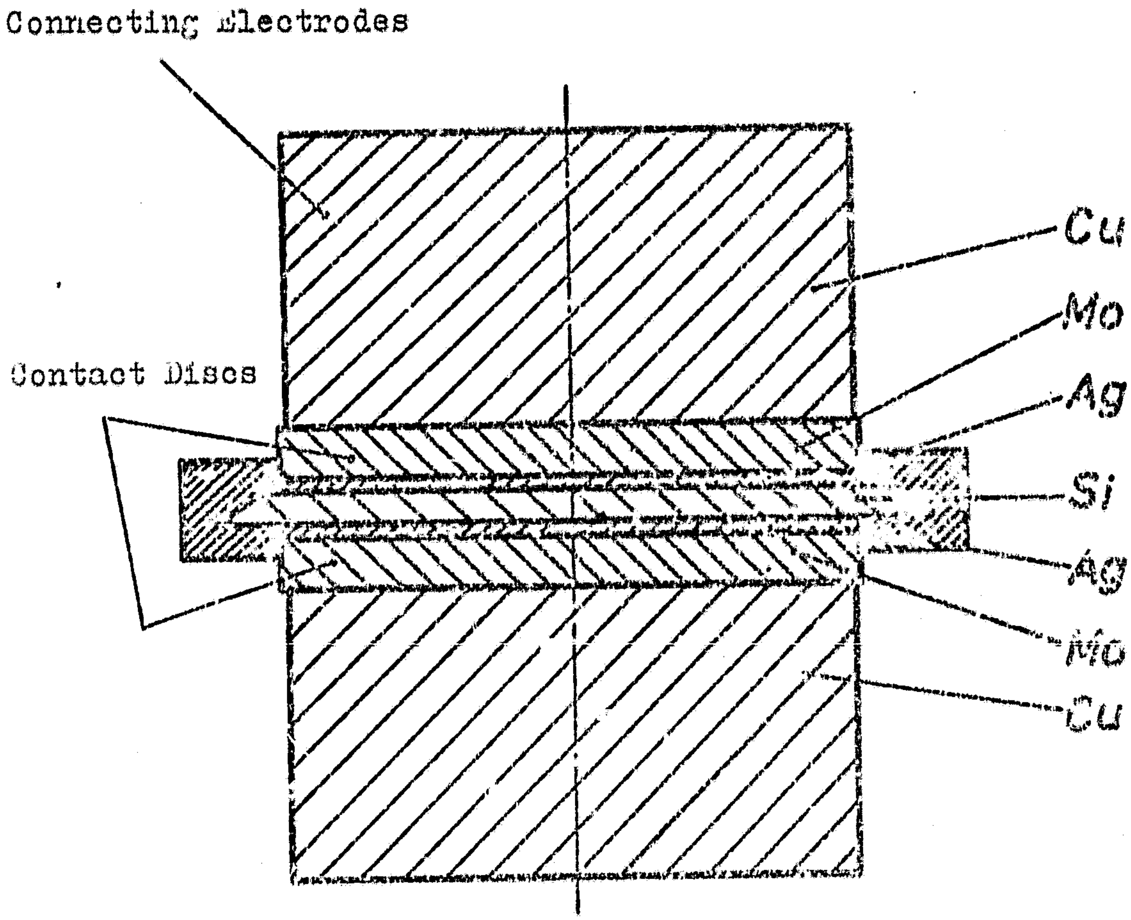

Fig. 1: Schematic Design of a Pressure Contact with fully Diffused Silicon Element.

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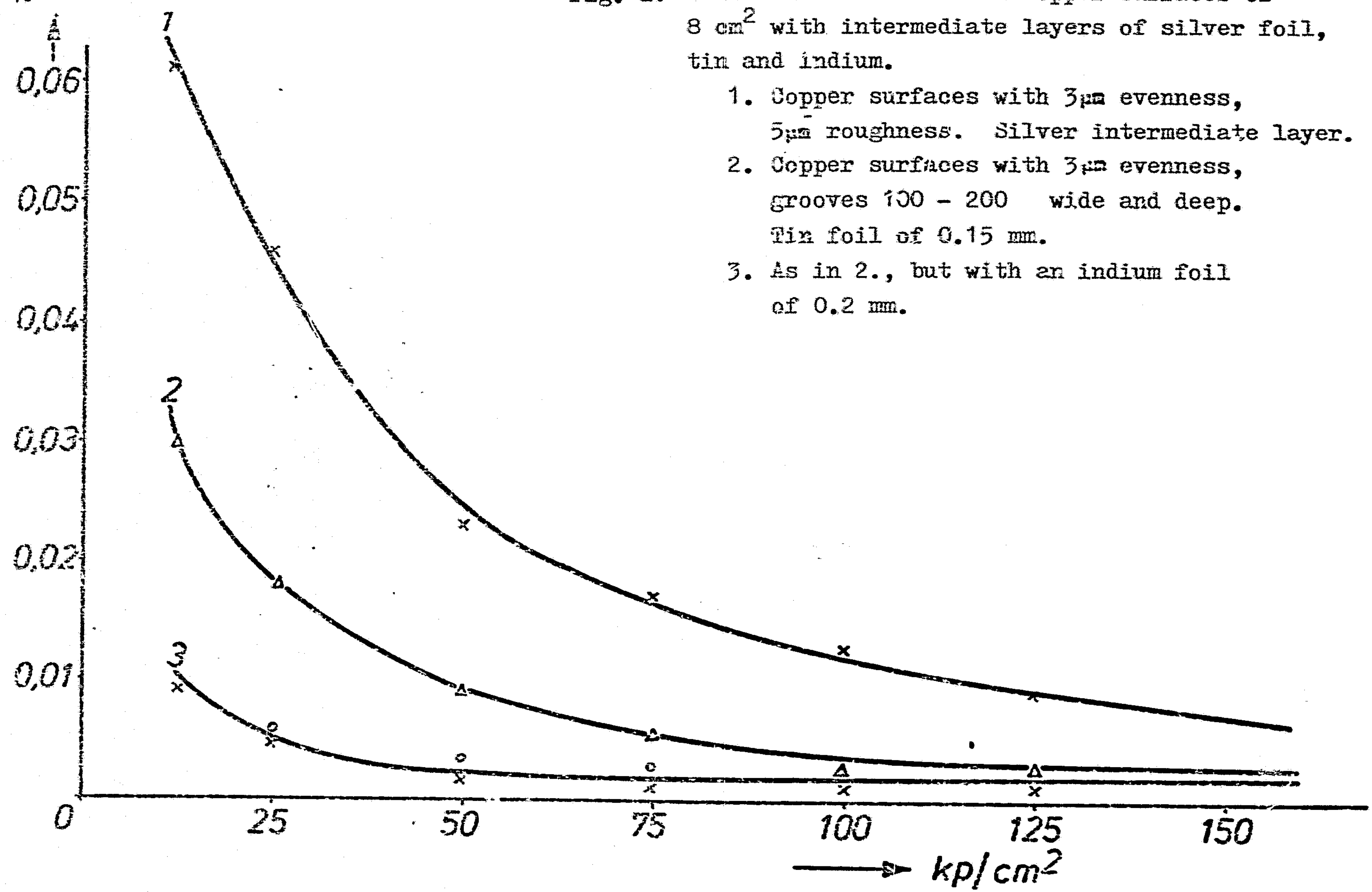
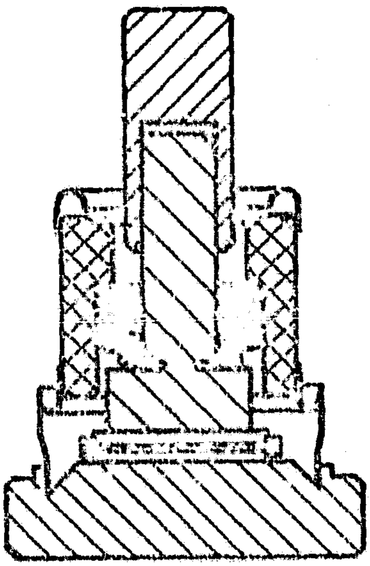
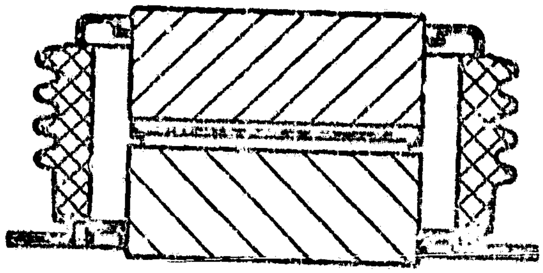


Fig. 2: Heat resistance between copper surfaces of 8 cm^2 with intermediate layers of silver foil, tin and indium.

1. Copper surfaces with 3µm evenness, 5µm roughness. Silver intermediate layer.
2. Copper surfaces with 3µm evenness, grooves 100 - 200 wide and deep. Tin foil of 0.15 mm.
3. As in 2., but with an indium foil of 0.2 mm.



System a



System b

Figure 3

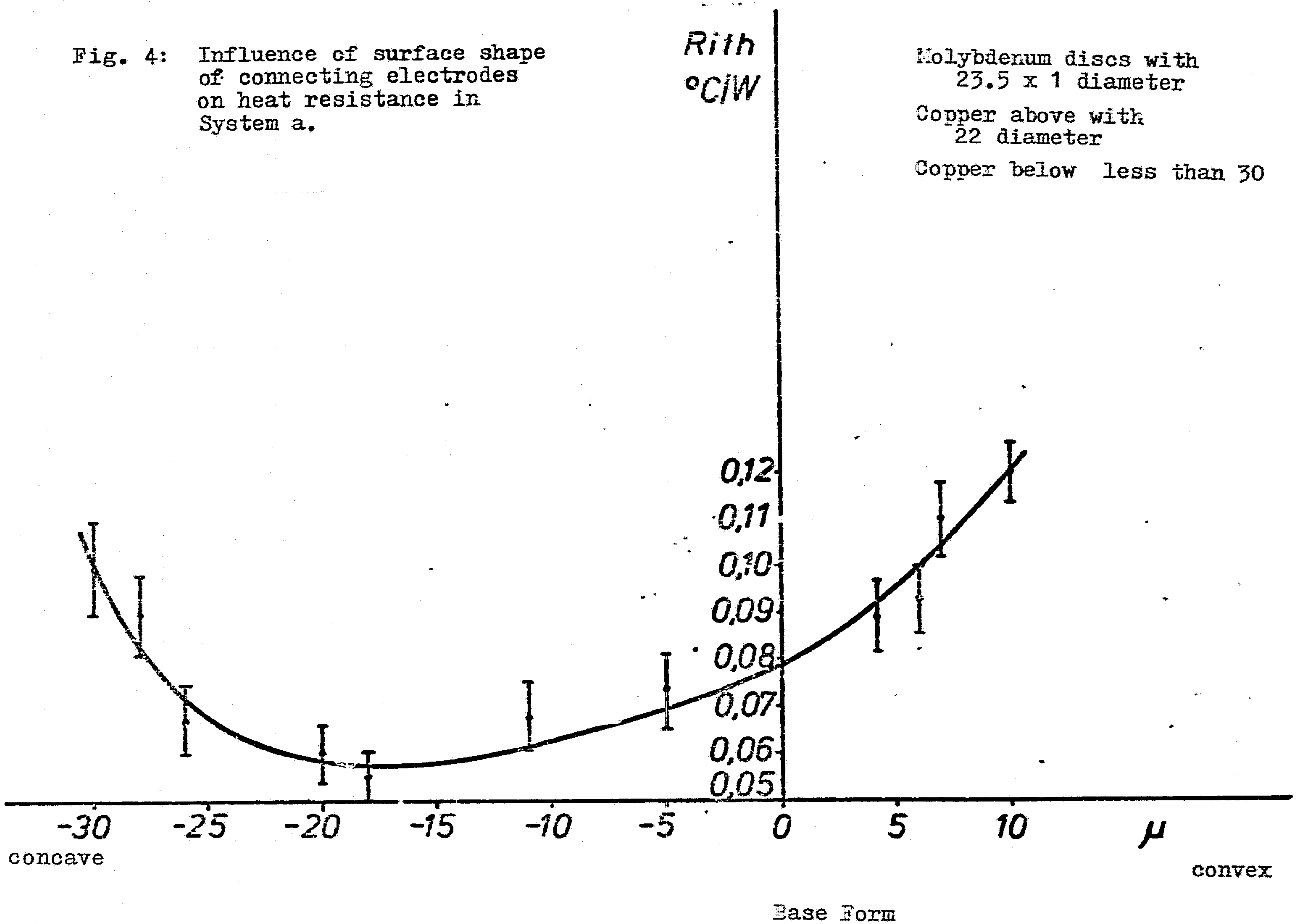


Fig. 4: Influence of surface shape of connecting electrodes on heat resistance in System a.

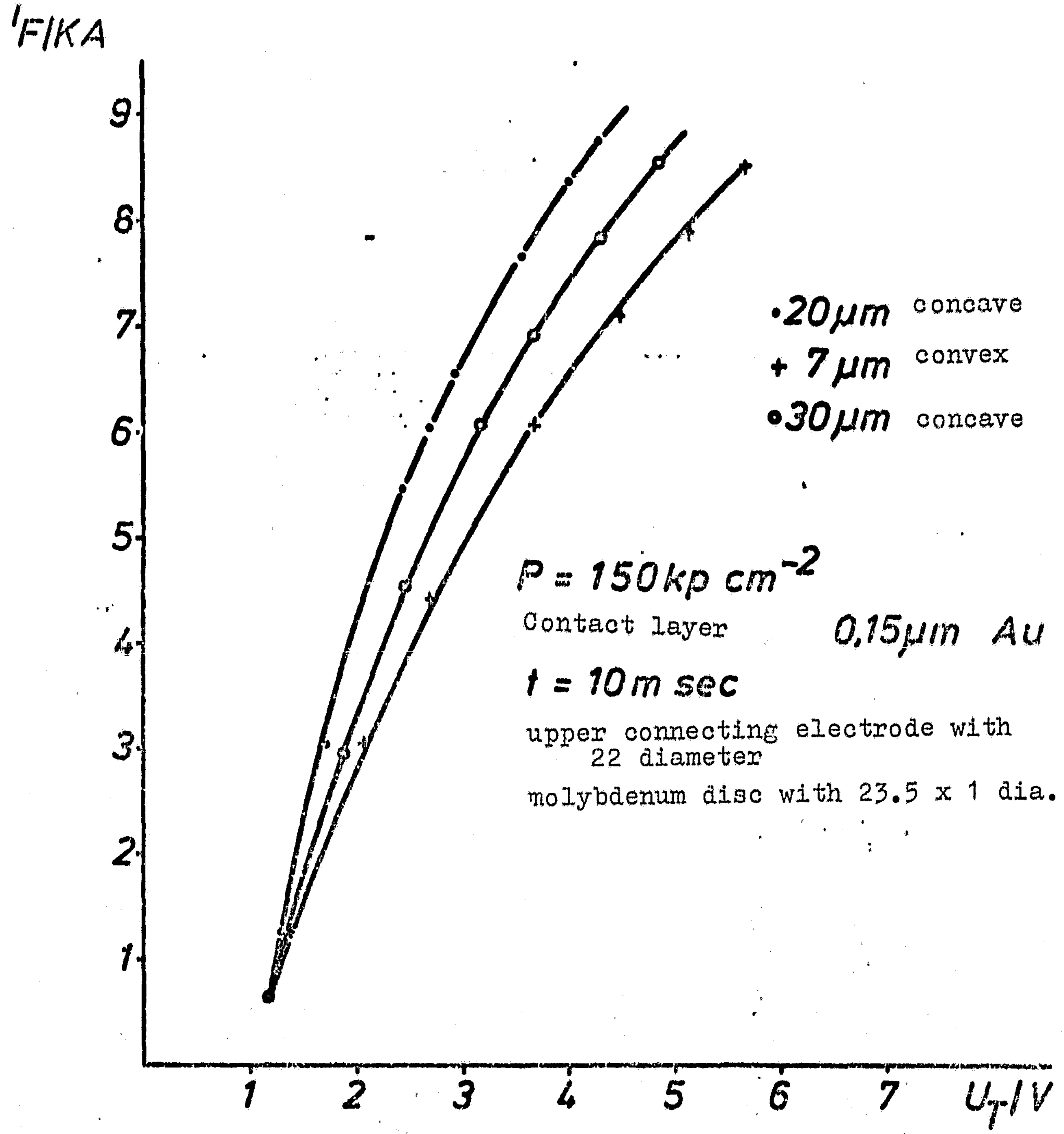


Figure 5: Influence of Surface Form on Forward Voltage Drop in System a

Layer of ordinary composition

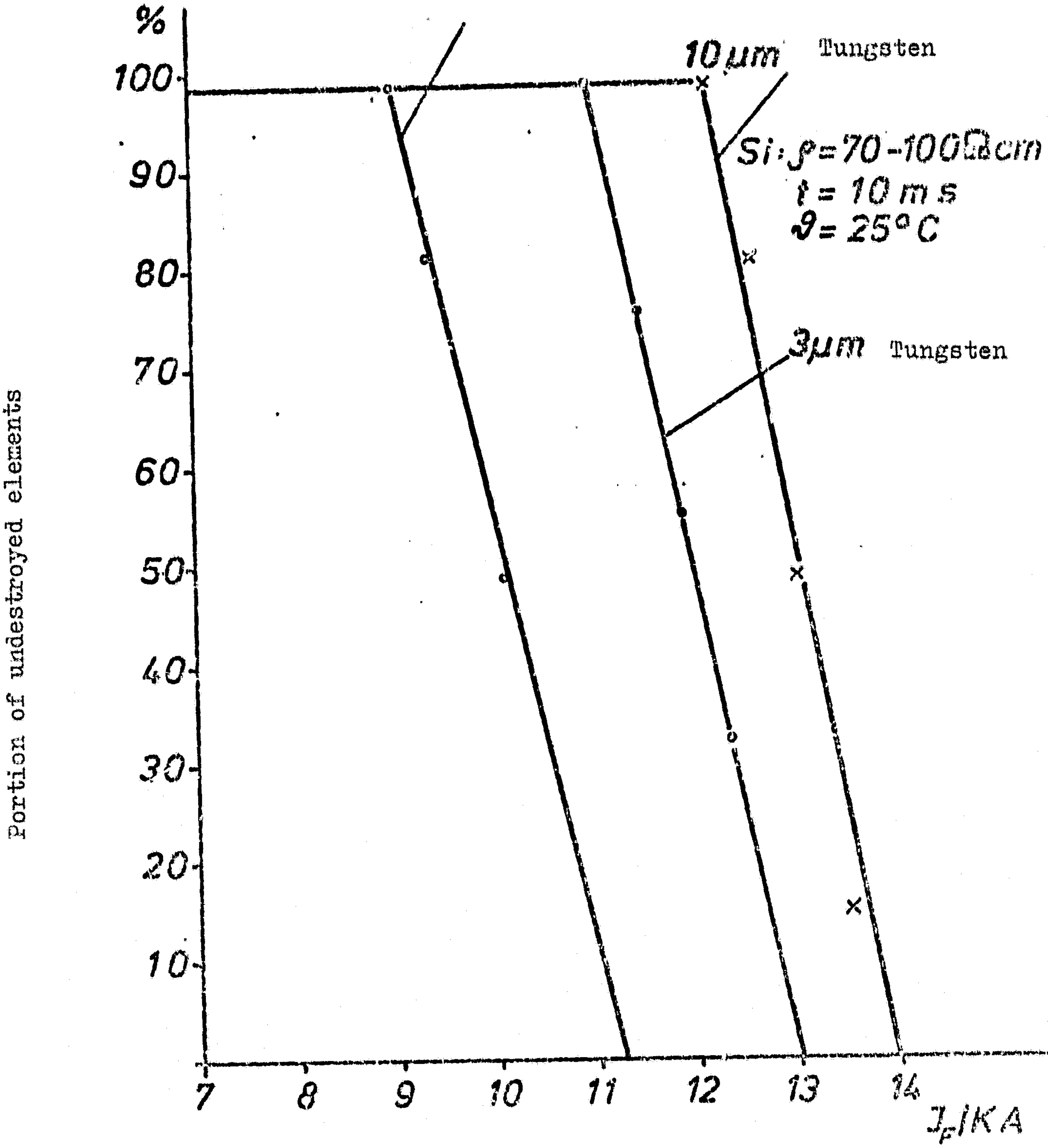


Fig. 6: Destruction Limits in the case of Surge Current as a Function of Thickness of Metallization Layer

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1 Nagel, G. and R. Weinsheimer, "Load Change Tests for Proof of Quality in Semiconductors," BBC-Nachrichten Vol. 57, Issue 5, 421 - 425 (1975).

2 Weinsheimer, R., Internal Report.