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ACCELERATED LIFETESTING AND FAILURE MODES OF THIN FILM
W CONTACTS ON SiGe THERMOELECTRIC ALLOYS

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ABSTRACT

The stability of sputtered thin film W contacts on heavily doped Si-Ge alloy has been determined from measurements of contact resistance versus time for aging temperatures in the range 550-725°C. Contact failure time has been found to obey an Arrhenius type relation with an activation energy of 76 ± 5 kcal/mole and a projected lifetime of over ten years at temperatures below 460°C. Contact resistance remains approximately constant for the first 80% of contact lifetime and then increases rapidly through several orders of magnitude. These large contact increases are accompanied by contact deadhesion and buckling. Comparison of this data with that from diffusion experiments indicates that the activation energy for contact failure is comparable with that for the initial stages of WSi_2 layer growth in W-Si systems.

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I. INTRODUCTION

The problem of stability in a metal-semiconductor contact system arises in cases where high temperature processing steps are used in device fabrication or when long term device operation at high temperatures is required. Interdiffusion and chemical reaction in the interface region may result in void formation in this region with an accompanying loss of contact adhesion and ultimately with complete contact unbonding. At some point in the diffusion/reaction process, the resistance of the contact will increase to an unacceptable value for proper device operation. The purpose of this study has been to determine the effective contact lifetime for sputtered thin film W contacts on Si-Ge alloy. These contacts were designed for use in a milliwatt thermoelectric power device with a hot junction temperature in the range 400-500°C. Contact reliability at these elevated temperatures was a primary concern since the device was intended to function unattended for many years.

It has been observed that appreciable atomic interdiffusion and reaction can occur in metal-Si contact systems at temperatures far below the eutectic temperature. For example, Hiraki, Nicolet, and Mayer¹ have shown by ion-backscattering that for Pt contacts on (111) Si, a layer of Pt 2000 Å thick will be completely converted to PtSi after a 2h anneal at 400°C although the Pt-Si eutectic temperature is at 980°C. Other common Si device metallization systems such as Al and Cr-Au also interdiffuse rapidly with Si at temperatures less than 400°C.

The use of refractory metal contacts such as W^{2,3,4} or Mo^{5,6} has frequently been suggested in cases where Si devices have to undergo high temperature processing steps such as chemical vapor deposition of SiO₂ subsequent to the contact metal deposition. The lowest eutectic temperature in the Mo-Si and W-Si systems is about 1400°C which is appreciably higher

than the eutectic temperatures of the other metal-Si systems mentioned above. Both W and Mo also have thermal expansion coefficients which are close to that of Si,² with the W coefficient being the closer of the two.

Bulk W contacts ~ 0.1 cm thick had previously been used by RC⁷ in the construction of Si-Ge thermoelectric modules for use in the SNAP 10A generator intended for space power applications. These disks were attached by a diffusion bonding process carried out near the Si-Ge melting temperature. Data from accelerated aging tests⁷ indicated that these contacts would survive for times > 5 years at temperatures $< 600^{\circ}\text{C}$. There was, however, no way that the results of these tests could be extrapolated to predict the aging characteristics of thin film W contacts on Si-Ge.

In this paper we shall discuss results from accelerated aging tests with sputter deposited W contacts on SiGe conducted in the temperature range $550-725^{\circ}\text{C}$. In these tests, the samples were annealed in vacuum with periodic sample removal for contact resistance measurement. The contact resistance versus time data has been used to derive a time to failure versus temperature relationship which could then be extrapolated to longer times and lower temperatures for prediction of contact lifetime at temperatures of actual interest. In the next section we shall discuss sample fabrication and in Section III the contact resistance measurement techniques are described. Experimental results are presented in Section IV and these results are used for life prediction in Section V. The results of our tests are compared to diffusion/reaction data in Section VI and the major conclusions of this study are summarized in Section VII.

II. SAMPLE DESCRIPTION

The thermopile samples used in this investigation consisted of large numbers of alternating 0.018 cm thick n and p-type polycrystalline Si-Ge (80 at. % Si) wafers separated and electrically isolated from each other by 0.0025 cm glass bonding layers. A schematic diagram of a thermopile contact is shown in Fig. 1(a) and a photomicrograph of a thermopile surface is shown in Fig. 1(b). Every other set of adjacent elements is interconnected at each end with a thin film contact bridging the glass layer as shown in Fig. 1. The net result is that all the thermocouples in the pile will be electrically connected in series. When a temperature gradient is established across the pile length, "hot" electrons will drift toward the cold end in the n-type elements and "hot" holes will drift in the same direction in the adjacent p-type elements. The net result is that current will flow in a thermopile of this type if the elements are all connected in series and a load is placed across the outermost cold end terminals.

The theory of thermoelectric power generation and basic criteria for desirable semiconductor materials have been reviewed in detail by Rosi.⁸ Basically, good thermoelectric materials will have: (1) high electrical conductivity to minimize internal ohmic losses, (2) low thermal conductivity in order to minimize the amount of heat lost by irreversible conduction from the heat source to the heat sink, and (3) a high Seebeck coefficient in order to maximize the induced voltage per unit temperature drop across the thermocouple. Degenerately doped alloy semiconductors are useful for satisfying these criteria because the alloying will result in decreasing the lattice contribution to the thermal conductivity without at the same time affecting the carrier concentration and hence the Seebeck coefficient.

The Si-Ge used in our specimens was prepared by a hot pressing technique developed at Sandia Laboratories.^{9,10} The general preparation procedure consists of initially chill casting the alloy and then planetary ball milling the casting into a powder. The powders with boron or phosphorous added for a doping level of $2 \times 10^{19} \text{ cm}^{-3}$ are then vacuum hot pressed for one hour at approximately 1280°C and 28,000 psi with a graphite-lined Mo-alloy die. The resultant alloys have a high degree of physical and chemical homogeneity with densities greater than 99.6% of theoretical. Typically, the alloy electrical and thermal properties are: Seebeck coefficient, $\alpha \sim 275 \mu\text{V}/^\circ\text{C}$, resistivity; $\rho_n \sim 5 \text{ m}\Omega\text{-cm}$, $\rho_p \sim 5.7 \text{ m}\Omega\text{-cm}$; Hall mobility $\sim 45 \text{ cm}^2/\text{V-sec}$; thermal conductivity, $\kappa \sim 5.1 \times 10^{-2} \text{ W}/^\circ\text{K-cm}$.

After the Si-Ge pressing has been completed, the pressed pucks are sawed into 0.018 cm thick wafers and the wafers are then assembled with the glass insulators into a thermopile by a high temperature bonding process. The end surfaces are then ground, lapped, and finally polished with powders sized down to $1/4\mu$ diamond. The surfaces are then chemically cleaned and the surface SiO_2 layer is removed with a dilute HF etch. It has been shown that pure SiO_2 will form on the surface of Si-Ge alloys at a rate close to that of pure Si if the Ge concentration is $\lesssim 20\%$.¹¹ Tungsten films 1-3 μm thick are then applied to the end surfaces of the thermopile by dc unbiased sputtering. The sputtering parameters used in all our depositions were: voltage - 4.5 kV, pressure - 3×10^{-2} Torr Ar, cathode-substrate spacing - 6.35 cm, sputtering rate - 167 $\text{\AA}/\text{minute}$, average substrate temperature - $385\text{-}440^\circ\text{C}$. The resultant films were in a state of compressive stress with a resistivity $\sim 35 \mu\Omega\text{-cm}$. This resistivity is in the range of those reported for W deposited by rf diode sputtering¹² but somewhat higher than the 10-17 $\mu\Omega\text{-cm}$ range reported for films deposited by low voltage triode

sputtering.¹³ The contacts are photolithographically defined after contact deposition.

Special samples have been fabricated for measurement of specific contact resistance as shown in Fig. 2. These samples consist of first Si-Ge wafers onto which a 2 μ m-W:1 μ m-Au metallization system is sputter deposited. The W-Au contacts are then photolithographically defined and electrical connections are made by thermocompression bonds as shown in Fig. 2, the contacts are squares, 0.051 cm on a side, and are located at the ends of the array. The .025 cm dots between the contacts are used in the specific contact resistance measurement and also for measuring the resistivity of the Si-Ge wafer.

III. CONTACT RESISTANCE MEASUREMENT

The total resistance of the W contacts shown in Fig. 1 is measured with a four point probe arrangement as shown in Fig. 3. The measurements were made at ~ 40 Hz to avoid any errors caused by stray thermoelectric voltages induced by small temperature differences across the contact. The voltage probes were placed as close to the end surface as possible, while the current probes were located about 0.25 cm away. Experiments with longer thermopiles indicate that the measured contact resistance; as calculated from $R_c = \Delta V/I$, where ΔV = measured voltage drop and I = measuring current, will decrease as the spacing between the current and voltage probes is increased along the element length until the spacing is ~ 2 cm. With our 0.25 cm spacing, all R_c measurements are about 25% too high and hence should be multiplied by a factor of 0.8 to get the actual contact resistance.

For the contact structure shown in Fig. 3, the total contact resistance R_c has contributions from both the specific contact resistance¹⁴ r_c of the W/Si-Ge interface and the sheet resistance R_b of the W bridge. The exact functional dependence of R_c on r_c and R_b depends on the values of r_c and R_b and the dimension L defined in Fig. 1(a). Although we have analyzed the situation in detail for the particular geometry under consideration,¹⁵ a simplified analysis of contacts on planar semiconductor devices by Barger¹⁶ can be applied to the problem with the result, applicable to our values of r_c and R_b ,

$$R_c = r_{cn}/Lw + r_{cp}/Lw + (2/3)R_b L/w + R_b t_g/w, \quad (1)$$

where r_{cn} and r_{cp} are the specific contact resistances of the n and p-type contacts, respectively, L = contact length over the Si-Ge elements, w = contact width, R_b = W sheet resistance, and t_g = glass insulator thickness. The first two terms are the specific contact resistance contributions of the W/Si-Ge contacts, the third term is the contribution of the W sheet resistance from the W over the Si-Ge and the last term is the sheet resistance contribution from W over the glass. The factor of 2/3 in the third term results from the fact that the voltage is not constant along the contact length in the Si-Ge region.

The W sheet resistance and the specific contact resistances can be measured independently and the results used in Eq. (1) to calculate a value of $\bar{R}_c$ which can be compared to the experimentally determined $\bar{R}_c$. The W sheet resistance was determined by conventional four point probe techniques on films deposited onto glass and Si substrates. The specific contact resistance was determined by passing a known current through one of the square contacts on the sample shown in Fig. 2 and then measuring the voltage drop between the contact and the adjacent small

marker dot on the substrate. The substrate contribution to the measured voltage drop was calculated and subtracted from the measured ΔV in order to find the voltage drop across the contact alone.

All the accelerated aging tests were performed in a vacuum furnace with the pressure maintained in the range $p \leq 5 \times 10^{-7}$ Torr. At this pressure, W surface oxidation is insignificant for the annealing times used in our tests.

IV. EXPERIMENTAL RESULTS

For the series of tests described in this report, samples were fabricated with 1, 2, and 3 μ m thick W contacts and then accelerated aging tests were conducted at 25°C intervals in the range $550^\circ\text{C} \leq T \leq 725^\circ\text{C}$. The different thicknesses were used to see if contact thickness was an important variable in the determination of contact lifetime. Typical results of these tests are shown in Figure 4-6 for the 575°C , 650°C , and 725°C tests respectively, where the average contact resistance for each channel, $\bar{R}_c$, is plotted vs. aging time. In one thermopile channel, there are 22 identical contacts at the hot end as shown in Fig. 1(b). The dashed line at $\bar{R}_c = 0.34 \Omega$ delineates the resistance at contact failure and corresponds to a value of $\bar{R}_c$ at which the generator power output drops below an acceptable value. It is evident from inspection of Figs. 4-6 that the average contact resistance is approximately constant for $\sim 80\%$ of the contact lifetime and then increases rapidly over several orders of magnitude at the end of life. The dependence of $\bar{R}_c$ on t was qualitatively similar in all the tests to that shown in Figs. 4-6. It can be seen that the exact choice of the failure resistance is not too important in the contact lifetime determination since the resistance is rising extremely rapidly near the failure point.

At the end of all the lifetests, the contacts were definitely unbonding from the Si-Ge/glass surfaces. Photomicrographs of typical contacts from the 650°C test are shown in Fig. 7. The scalloped appearance of the 1 μ m contacts indicated that the films have expanded with complete loss of adhesion in certain regions. The 2 μ m contacts in Fig. 7(b) have not lifted off although the average resistance of these contacts had increased to over 4 Ω as shown in Fig. 5. Fig. 7(c) shows that contact lift off had started on the 3 μ m contact sample but only over the p-type Si-Ge elements. In general, contact lift off occurred initially over the p-type elements in all of the tests.

An electron microscope photograph of a 3 μ m contact aged at 650°C for 10h is shown in Fig. 8. The debonding and buckling of the W contact is clearly evident in this figure. The portion of the contact over the glass insulator is still bonded strongly. If a contact of this type is pulled from the substrate it breaks at the glass/Si-Ge boundary.

The specific contact resistance measurements on wafer samples indicated that, for Si-Ge doped to $2 \times 10^{19} \text{ cm}^{-3}$ phosphorous or boron, the n and p-type specific contact resistances were, $r_{cn} = (1.12 \pm 0.05) \times 10^{-4} \Omega\text{-cm}^2$ and $r_{cp} = (6.2 \pm 2) \times 10^{-5} \Omega\text{-cm}^2$, respectively. These values were about a factor of 10 larger than those reported by Sinha for W/PtSi contacts on similarly doped $\langle 111 \rangle \text{Si}$ ¹⁷ but are in reasonable agreement with the values reported by Hooper, Cunningham, and Harper¹⁸ for evaporated Mo-Si(.005 $\Omega\text{-cm}$) contacts. The W sheet resistance for 3 μ m contacts was $R_b \simeq 0.15 \Omega/\text{sq.}$ and this value remained essentially unchanged throughout contact lifetime. Using the measured values of r_{cn} , r_{cp} , and R_b in Eq. (1) for R_c yields the predicted beginning of life value, $R_c = 0.045 \Omega$. The average initial $\bar{R}_c$ measured values were in the range 0.08-0.12 Ω when corrected by the 0.8 probe spacing factor.

Thus, on the average, there appeared to be some extra resistance associated with the contacts which could not be accounted for with the simple model represented by Eq. (1), although the smallest R_c values in the contact resistance distribution were close to the theoretically predicted one.

The spread in initial $\bar{R}_c$ values shown in Figs. 4-6 for the different contact thicknesses is felt to be associated with the different deposition parameters used in the various sputtering runs and not solely with the contact thickness. A change from 3 μm to 1 μm contact thickness will only add $1.4 \times 10^{-3} \Omega$ to the total contact resistance. The samples with 3 μm contacts saw an average temperature of 440°C during sputtering while those with 1 and 2 μm contacts saw 385-410°C during sputtering. In general, we have found that higher deposition temperatures lead to lower initial contact resistances.

V. LIFE PREDICTION

The time t_F of contact failure was estimated from plots of the $\bar{R}_c$ versus t data such as those shown in Figs. 4-6. Since there is no exact way to make this determination, there is some uncertainty associated with the t_F determination. The data from the tests with 3 μm contacts is shown on an "Arrhenius" $\log t_F$ versus $1/T$ plot in Fig. 9. The extremes of the data point bars correspond to the minimum and maximum estimated values of t_F while the midpoint represents the average estimated t_F for a given temperature. The solid line represents the least squares fit of the form,

$$\log t_F = A(10^3/T) + B, \quad (2)$$

to the average t_F data points, where T = absolute temperature. If this equation is rewritten in the form,

$$t_F = t_{Fo} \exp(Q/RT) , \quad (3)$$

where t_{Fo} = constant, R = universal gas constant, and Q = activation energy, then Q and A are related to each other by,

$$Q(\text{kcal/mole}) = 4.58A(^{\circ}\text{K}) . \quad (4)$$

The estimated standard error in A is calculated via the standard prescription,¹⁹

$$\delta A = s / [\sum_i (10^3/T_i - \overline{10^3/T})^2]^{1/2} , \quad (5)$$

$$s^2 = \left(\sum_i \left\{ (\log t_{Fi}) - [A(10^3/T_i) + B] \right\}^2 \right) / (n - 2) , \quad (6)$$

where $(10^3/T_i, \log t_{Fi})$ represents the coordinates of the i^{th} of n points. The numerical results from the analysis are shown in Table I.

Table I
Results of Least Squares Linefit to
Experimental $\bar{R}_c$ Versus t Data Points

	1 μm contact	2 μm contact	3 μm contact
$A(^{\circ}\text{K})$	16.436	15.534	17.693
$\delta A(^{\circ}\text{K})$	0.612	1.098	0.635
$Q(\text{kcal/mole})$	75.28	71.10	80.98
$\delta Q(\text{kcal/mole})$	2.80	5.02	2.90
B	-16.953	-16.098	-18.337

In Table I, Q and δQ have been calculated from δA with Eq. (4). From this table it is evident that the spread in Q values for the different contact thicknesses is somewhat larger than the uncertainty δQ associated with contacts of a given thickness.

To indicate the relative effect of the variation of these parameters on contact lifetime, we have calculated the maximum permissible temperatures for 1h and for ten year operation from Eq. (2). These results are shown in Table II.

TABLE II
Temperatures for 1h and Ten Year Operation

Contact Thickness (μm)	$T(^{\circ}\text{C})$ -1h Operation	$T(^{\circ}\text{C})$ -Ten Year Operation
1	697	479 (472)
2	692	466 (462)
3	692	487 (486)

The temperatures in parenthesis in the third column of Table II were calculated using A and B values found from a fit using the minimum estimated t_F values and hence represent a worst case estimate of the maximum temperature.

The estimated standard error for the slope, Eq. (5) and a similar quantity for the average of the data, $\overline{\log(t_F)}$, can be used to find confidence limits for the least squares fit.¹⁹ In accelerated lifetesting, the "worst case" line fit will be the one with the smallest slope and the smallest value of $\overline{\log(t_F)}$ since this line will intersect the horizontal lifetime line at the lowest temperature. The 99.9% "worst case" confidence limit line is shown in Fig. 9. This line leads to an expected ten year lifetime at temperatures $\leq 450^{\circ}\text{C}$. An analysis of the residuals,¹⁹ $e_i = \log(t_{Fi}) - A(10^3/T_i) - B$, for the data taken in these tests indicates that the residuals appear to be random and uncorrelated as required by the standard theory of confidence interval estimation.

VI. COMPARISON WITH DIFFUSION/REACTION DATA

The ion-backscattering experiments of Borders and Sweet²⁰ on diffusion/reaction in thin W films deposited onto Si-Ge substrates have shown that there is little or no W-Ge interdiffusion at high temperatures and that Si appears to diffuse into the W region and form a WSi_2 reaction zone there. At the time this study was performed, it was found that the reaction rate data was not very reproducible. It was felt that the presence of an SiO_2 layer at the Si-Ge surface acted as a diffusion barrier and that different SiO_2 thicknesses on the various samples were responsible for the variation in observed reaction rates. This effect was later confirmed in experiments on reaction in W-Si systems by Border and Sweet²¹ and by Locker and Capio.²² Thus, it is difficult to compare absolute reaction rate data directly to our data. It is, however, possible to compare the activation energies from various diffusion and lifetest experiments with our data. Such a comparison is shown in Table III.

The low activation energies shown in the first three entries of Table III were all determined in experiments in which the diffusion of Si through the WSi_2 layer to the W interface was the rate limiting step. Other experiments^{21,22,26} suggest that prior to the onset of diffusion controlled layer growth, there is a period of time in which the WSi_2 layer grows as t^n where $n > \frac{1}{2}$. This initial power of n in the growth law may be the result of the reaction zone growth being limited by the rate at which the reaction $\text{W} + 2\text{Si} \rightarrow \text{WSi}_2$ can occur at the zone front or it may be caused by the presence of an SiO_2 diffusion barrier on the Si or SiGe surface. The large activation energies shown in entries 4-6 of Table III are probably associated with the initial growth rate and not the diffusion limited growth rate.

TABLE III

Experimental Activation Energies for WSi_2 Formation in W-Si Systems and for Failure of W Contacts on SiGe

Entry	Author/Ref.	Expt. System	Temp Range ($^{\circ}\text{C}$)	Q(kcal/mole)	Q(eV/atom)
1	P. R. Gage, R. W. Bartlett/Ref. 23	Bulk W-powder Si	855-1100	50*	2.2
2	V. I. Zmii A. S. Seryugina Ref. 24	Plate of single crystal Si against plate of 99.95% pure W	1200-1350	48*	2.1
3	N. Hashimoto Ref. 25	$\langle 111 \rangle$ Si crystal wafer - CVD W	1040-1330	44*	1.9
4	A. K. Sinha, T. E. Smith Ref. 26	$\langle 100 \rangle$ Si crystal wafer PtSi (900Å)-W(sputtered, 2000Å)	690-840	102.3***	4.4
5	L. D. Locker, C. D. Capio Ref. 22	$\langle 100 \rangle$ Si crystal wafer W(sputtered, 2200Å)	730-850	65 ± 5 ***	$2.8 \pm .2$
6	J. A. Borders, J. N. Sweet Ref. 21	$\langle 111 \rangle$ Si crystal wafer W(sputtered, 2200 Å)	625-750	$63 - 71$ ****	2.7 - 3.1
7	J. P. Dismukes, F. D. Rossi Ref. 7	Bulk W contacts on SiGe alloy (SNAP)	750-850	62	2.3
8	This Work	Sputtered W contacts on SiGe Thermopiles	550-725	71.1-81.0*****	3.1-3.5

*Determined from microscope photographs of WSi_2 layer thicknesses.

**Determined from x-ray diffractometer observation of WSi_2 layer.

***Determined from He ion backscattering spectra.

****Determined from contact resistance measurement.

More recent ion-backscattering studies of contacts aged to the failure times shown in Fig. 9 indicate that the average WSi_2 layer thickness at contact failure was $\lesssim 200 \text{ \AA}$, the limit of resolution for this particular technique. Thus, the high activation energies which we have observed are consistent with the hypothesis that the activation energy associated with the initial layer growth rate effectively determines the contact lifetime.

VII. DISCUSSION AND CONCLUSIONS

From the discussion and data in Section V, we can see that the experimental dependence of failure time on temperature is in excellent agreement with the Arrhenius relationship, Eq. (2). The increase in initial contact resistance near end of life can be attributed to loss of contact area, as shown in Figures 7, 8 and/or to an increase in specific contact resistance. The fact that contacts to p-type elements are in general less stable than those to n-type elements indicates that the presence of impurity atoms at the interface plays a major role in determining the reaction kinetics and hence the results of this study would not necessarily be quantitatively applicable if the Si-Ge doping was changed.

The results shown in Tables I and II indicate that the contact thickness had a noticeable, although not drastic, effect on contact lifetime. Without further experimentation, it is impossible to say whether the observed differences were the result of the different film thicknesses and deposition conditions or a result of the different Si-Ge thermopiles used as substrates. In all cases, however, the p-type Si-Ge/W contact areas showed evidence of reaction prior to the n-type Si-Ge/W contacts and the

stress exhibited by the W films was always compressive. It is interesting to note that in the 575°C test, the 2 μm contact failure time was roughly half that for the 1 μ or 3 μ contacts (Fig. 4). However, photographs of typical 575°C contacts indicate much less apparent reaction for the 2 μm contacts than for the 1 μ or 3 μ contacts.

The effect of substrate temperature and film thickness on film stress in sputtered W films on Si substrates has been studied by Sun, Tisone, and Cruzan.¹³ They found that, for a substrate temperature of 370°C, the compressive stress was approximately constant for films thicker than 1 μ although their data is only for a maximum W thickness of 1.5 μm . For 0.5 μm films they found that the magnitude of the compressive stress decreases rapidly as substrate temperature increases.

In our experiments, the average deposition temperatures for the 1 μm and 3 μm contact samples were 400°C and 430°C, respectively. The shorter period and more pronounced nature of the 1 μm contact buckling as compared to that of the 3 μm contacts might be due to higher stress levels existing in the 1 μm contacts. This would be consistent with the experiments of Sun, et al., although a close examination of their data shows only an $\sim 2\%$ change in stress for a substrate temperature change from 400°C to 430°C.

The absence of contact buckling in the case of 2 μm contacts is puzzling. The W films for the 2 μm contacts were sputtered on samples which rested on a heated flat plate while the samples with 1 μm and 3 μm contacts were placed in a special heated thermopile sputtering fixture for the deposition. It is possible that the different conditions prevailing at the sample surface in the anode region in the two cases resulted in different levels of stress in the 1 μm and 3 μm films as compared to the 2 μm film.

A general conclusion which can be drawn from this study is that thin film W/Si-Ge and W/Si contact/metallization systems possess excellent stability against degradation during prolonged operation at temperatures $T \lesssim 450^\circ\text{C}$. However, the exact quantitative dependence of failure time on aging temperature will depend on the particular system in question, and in all probability the aging characteristics for somewhat different systems will vary from those which we have reported here.

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$$L = 0.013 \text{ cm}$$

$$W = 0.34 \text{ cm}$$

$$t_g = 2.54 \times 10^{-3} \text{ cm}$$

TOP VIEW OF TUNGSTEN CONTACT ON THERMOPILE

TUNGSTEN CONTACT

(a) TOP VIEW OF THERMOPILE SAMPLE

(b) SIDE VIEW OF THERMOPILE SAMPLE

$$R_c = r_{cn}/LW + r_{cp}/LW + (2/3)R_b L/W + R_b t_g/W$$

**SCHEMATIC OF 4-POINT PROBE CONTACT
RESISTANCE MEASUREMENT**

**AVERAGE CONTACT RESISTANCE VS AGING TIME
FOR 575°C LIFE TESTS**

**AVERAGE CONTACT RESISTANCE VS AGING TIME
FOR 650°C LIFE TESTS**

**AVERAGE CONTACT RESISTANCE VS AGING TIME
FOR 725°C AGING TESTS**

(a)

1 μ CONTACTS

(b) 2 μ CONTACTS

3 μ CONTACTS

(c)

W CONTACTS AGED
AT 650° C FOR
9.7 H

W CONTACT

SiGe

GLASS INSULATOR

25 μm

CONTACT UNBONDING

**FAILURE TIME VS TEMPERATURE DATA FOR LIFE TESTS
WITH 3 μ m CONTACT SAMPLES**