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MECHANICAL STABILITY OF DIODES FOR CRYOGENIC 80-120 GHZ MIXER

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INTRODUCTION

Schottky barrier GaAs diodes are assembled with quartz microstrip r.f. chokes onto a quartz substrate for operation in the cryogenic 80-120 GHz mixer. These diodes exhibit finite operational life with the dominant failure mode being open circuit and the secondary mode being degradation from whisker punch through. The past seven weeks have been spent assembling replacement diodes for use in Tucson. Emphasis has been on obtaining units that will cool without failing and will demonstrate good noise performance. During this period, all phases of diode assembly and mounting have been reviewed and several factors crucial to mechanical stability under cryogenic operation have been illuminated. This memorandum documents and updates diode construction, materials, and assembly procedures related to achievement of stability and reliability.

1.0 Diode-Choke Subassembly

The GaAs Schottky barrier diode is mounted and contacted in the choke subassembly shown in Figure 1.

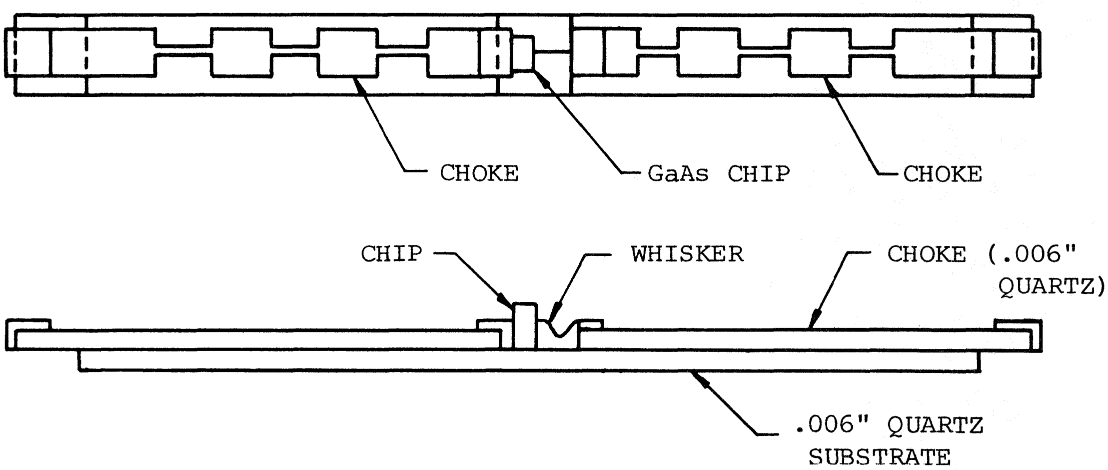

Figure 1. Diode-Choke Subassembly

The quartz chokes and substrates are 6 mils thick by 16.5 mils wide. The substrate is 230 mils long and the individual chokes are each 125 mils long. Gold ribbon is first ultrasonically bonded to the choke end sections and folded over the end to provide a surface for electrical contact. The GaAs chip is soft soldered directly to the inner (low impedance) end (folded over gold ribbon) of one choke.

A 10 mil long phosphor bronze contact whisker 0.5 mil in diameter is ultrasonically bonded to the inner end of the other choke on the top surface of the gold ribbon (the gold is not folded over the ends of the whisker choke). The whisker is fabricated of annealed phosphor bronze wire which has been electrolytically pointed on one end and gold plated but is not bent to its final configuration prior to mounting on the choke end. After the whisker is ultrasonically bonded, the bond is soldered over to provide additional mechanical strength.

The whisker is bent to final form by hand using a scalpel blade and simple alignment jig. The bending is such that the whisker goes down leaving the choke end, then up forming a vee, and finally back level pointing directly away from the choke end at the level of the (upper) choke surface.

The choke with diode chip attached is aligned and firmly bonded to the quartz substrate using Eastman 910 contact cement. The back section of the choke overhangs the substrate by 10 to 12 mils for subsequent proper alignment of the diode in the waveguide section. A special fixture is used for "whiskering" (contacting) the diode. The substrate with chip-choke is mounted in the fixture as shown in Figure 2.

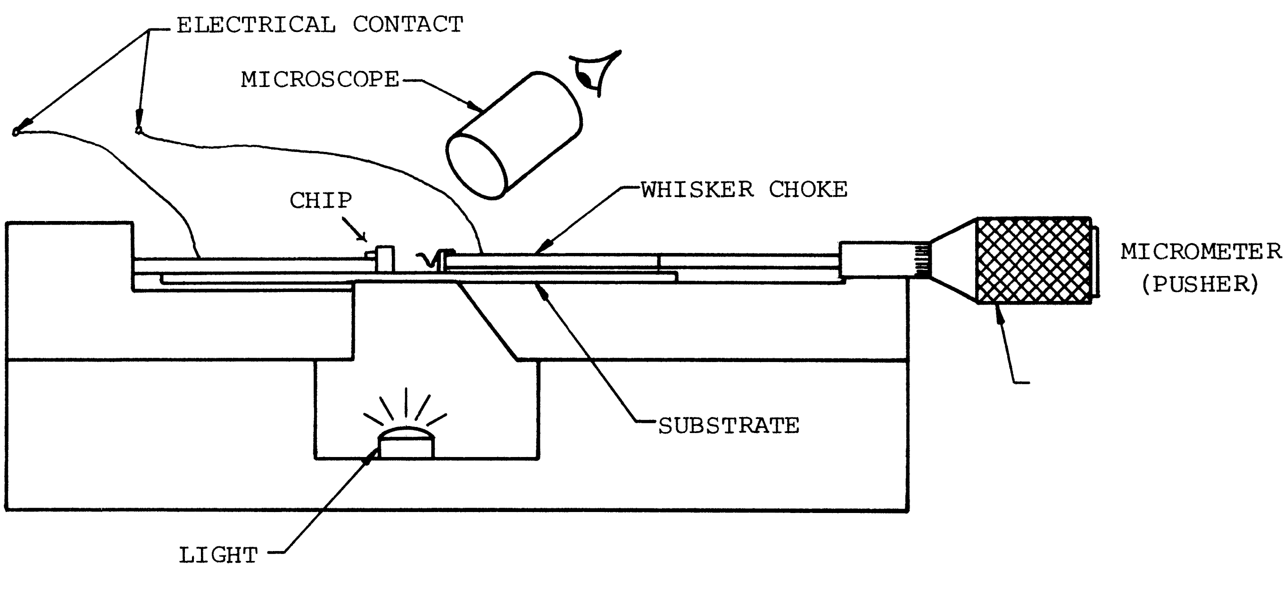

Figure 2. Whisker Contacting Apparatus

Electrical contact is maintained to both choke sections during the contacting operation. Progress is monitored visually via the microscope and electrically by a curve tracer connected across the chokes. Once the whisker contacts a Schottky dot the diode forward characteristic may be observed on the curve tracer for determination of η and R_S. If the diode is satisfactory, an additional whisker deflection of 1.5 μm is inserted at the micrometer and a drop of Eastman 910 is touched to the interface between the choke and substrate where surface tension causes this to wet the entire interface and effect a strong bond. The diode-choke subassembly is subsequently removed from the whiskering jig and is complete and available for further testing in a mixer block.

2.0 Diode-Mixer Block Assembly

The diode-choke subassembly is mounted in a channel in the mixer block in such a manner that the chip and whisker are located across the waveguide. The subassembly is constrained in position by an opposing indium land and bellows in one direction and by a spacer and bellows in the other direction as shown in Figure 3.

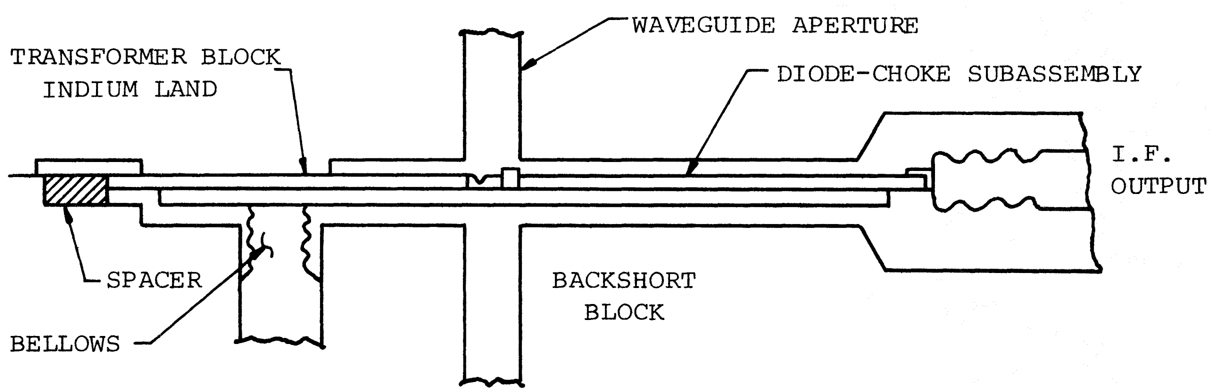

Figure 3. Diode-Choke Subassembly Mounted in Mixer Block

There is no provision for constraint in the third direction other than the lateral clearance of the choke subassembly in the channel in the mixer block which is about 1 mil on either side.

Two similar but different assembly techniques have been followed historically for placing and mounting the diode-choke subassembly in the mixer block. In the first technique, the choke subassembly is laid into the backshort block with the bellows retracted to the flush position. Then the i.f. connector is tightened compressing the i.f. bellows against the end of the choke. Finally the transformer block is brought into position and tightened and the backshort side bellows is tightened to hold the whisker side choke in contact with the built-up indium land. This assembly procedure has the disadvantage that the choke assembly is deflected by the final bellows tightening and that the i.f. end of the choke is not centrally aligned within the channel. The deflection tends to bend the quartz in a direction that reduces whisker deflection.

The second assembly procedure also starts with the choke subassembly in position in the backshort block with the bellows retracted. However, the transformer block is immediately clamped into position and the block is upended so that the i.f. end of the choke is visible through a binocular microscope. The bellows is tightened gradually until the end of the choke subassembly is observed to move away from the backshort block. The bellows is then given a final deflection of 1/2 to 3/4 turn which is about 12 to 18 mils (@ 25 mils/turn) of which 3 to 4 mils is free travel to bring the upper surface of the choke into contact with the indium land (which must be rolled flat beforehand). A disadvantage of the second assembly procedure is that the choke subassembly is unsupported mechanically over the distance between the indium land and the i.f. bellows contact.

3.0 Deflections, Constraints and Cryogenic Coolability

Problems of diode open circuits have arisen both before and after assembly into the mixer block and both before and after cooling to 77°K. In general, however, the most difficult portion of the task is to get the diode to cool to 77°K without opening once mounted in the block. Several areas of importance that were uncovered during attempts to fabricate and mount diodes that cooled successfully will be discussed.

3.1 Bad Whiskers or Bad Glue?

Two potential problem areas that arose early in the study and were subsequently eliminated were bad whiskers and bad glue. A bad whisker is one which distorts drastically upon cooling. It is apparently possible to make very bad whiskers using unannealed wire. We confirmed the fact that the whiskers being used were OK by fabricating a new batch using wire that was definitely annealed without any detectable improvement in the statistics of fabricating diodes that would cool.

Bad glue would be Eastman 910 that would not set up hard due to age and would subsequently slip or flow under the shear stress and thus alter the critical alignment and deflection between whisker and chip. We changed glue lots without noticeable improvement in the situation. It is important to store the Eastman 910 under refrigeration and to verify the bond quality if in doubt.

3.2 Quartz Deflection Required for Open Circuit

The amount of angular deflection required within the quartz substrate to lift the whisker free of the diode contact and produce an open circuit was calculated for the geometry shown in Figure 4.

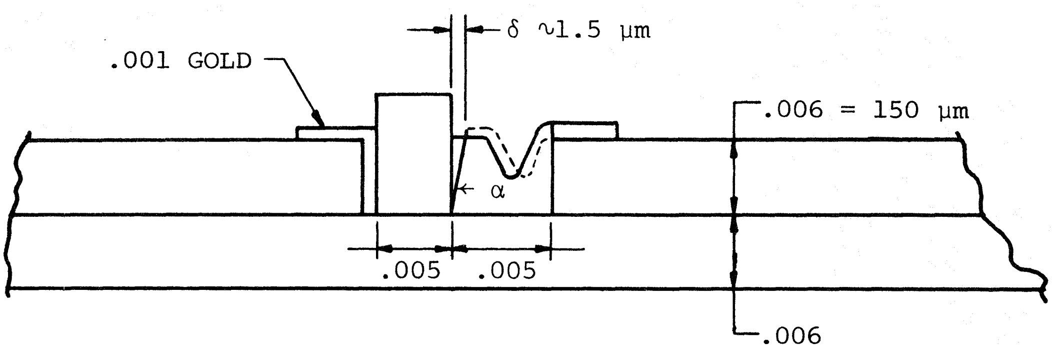

Figure 4. Angular Deflection Required to Produce Diode Open Circuit

The angle α is determined by

$$\alpha \approx \tan \alpha = \frac{1.5\ \mu m}{150\ \mu m} = .01\ \text{rad} \cong .57^\circ$$

The 1.5 μm backwards motion of the whisker assumed in the above calculation is based upon the initial whisker deflection of 1.5 μm after electrical contact is established. However, several factors act to reduce the amount of backwards whisker motion required to open circuit the diode. These will be discussed individually with prescribed remedies or improvements below.

3.3 Substrate Flexure in the Whiskering Jig

Curvature of the quartz substrate in the whiskering jig contributed an error to the initial amount of whisker deflection. Pressure is applied to the top surface of the whisker choke shown in Figure 2 during the whisker contacting process in order to establish electrical contact and to hold the choke in good mechanical contact with the substrate. A vertical deflection in the center of the substrate of .001" (25.4 μm) corresponds to an angular deflection of about 8.7×10^{-3} rad or an error of whisker deflection of about 1.3 μm. Obviously the substrate deflection in the whiskering jig must be kept well below this value. The present jig has been improved in this area but would need a complete redesign to effectively eliminate the slight backing off of the whisker which occurs when the diode is removed from the jig. A visual estimate of vertical deflection with the present jig is 2.5 to 5 μm which produces 0.13 to 0.26 μm of whisker "back up". This effect is particularly pernicious since we must avoid overdeflection to prevent punch through and whisker spreading.

3.4 Differential Contraction Upon Cryogenic Cooling

Differential thermal contraction between the quartz substrate and the elements comprising the diode contacting structure will modify the whisker deflection at cryogenic temperatures. The geometry is as shown in Figure 4. The thermal expansion or contraction is expressed as

$$\frac{\delta \ell}{\ell} = K \, \Delta \, T \, , \qquad \delta \ell = \ell \, K \, \Delta \, T$$

For cooling from room temperature (300°K) to 15°K we have $\Delta T = 285$°K and obtain the contractions given in Table 1.

Table 1 - Thermal Contraction of Diode Contact

MATERIAL	ℓ(μm)	K(x 10^{-6}°C^{-1})	$\delta\ell$(μm)
Quartz	279.4	.256	.0204
Gold	35.4	13.2	.0956
GaAs	127.0	6.0	.2172
Phos. bronze	127.0	18.9	.6841

The net differential contraction obtained by substacting the contraction of the quartz from the sum of contractions of the gold, GaAs, and phosphor bronze is 0.98 μm.

When added to the small whisker retraction resulting from deflection in the whiskering jig, the total whisker retraction is between 1.11 μm and 1.24 μm. Since we only started with 1.5 μm of whisker deflection, the situation is beginning to look serious already (and there are further retractions to come).

The principal contribution to whisker retraction upon cooling is shrinkage of the phosphor bronze whisker itself (0.684 μm). Or, alternately, the quartz may be considered the culprit since it barely shrinks at all. Evidently, the differential contraction can be reduced by changing either the quartz or the whisker to a more suitable material. Other choices for whisker material should have smaller thermal expansion coefficients such as tungsten, tantalum, or molybdenum. Unfortunately, these materials are also stiffer (higher Young's modulus) and therefore increase the risk of punching the whisker through the contact to ruin the diode. However, choice of an elemental metal whisker as opposed to an alloy material may be preferable to avoid phase or structural changes upon cooling. The other alternative, of modifying the quartz substrate to a more suitable material appears immediately promising. Glasses are available with expansion coefficients to match the composite coefficient of the gold-GaAs-whisker combination ($K_{eff} \approx 12.5 \times 10^{-6}$ presently). The use of a thermally matched glass could practically eliminate the component of whisker contraction due to cooling.

3.5 Plastic Deformations at the Whisker Tip

Another factor affecting the residual whisker deflection available for maintaining electrical contact to the chip is plastic deformation that occurs at the whisker tip during contacting. The gold of the diode contact is much softer than the spring wire as is the gold plate on the whisker itself. The author's conception of the plastically deformed tip geometry after whisker deflection is shown in Figure 5.

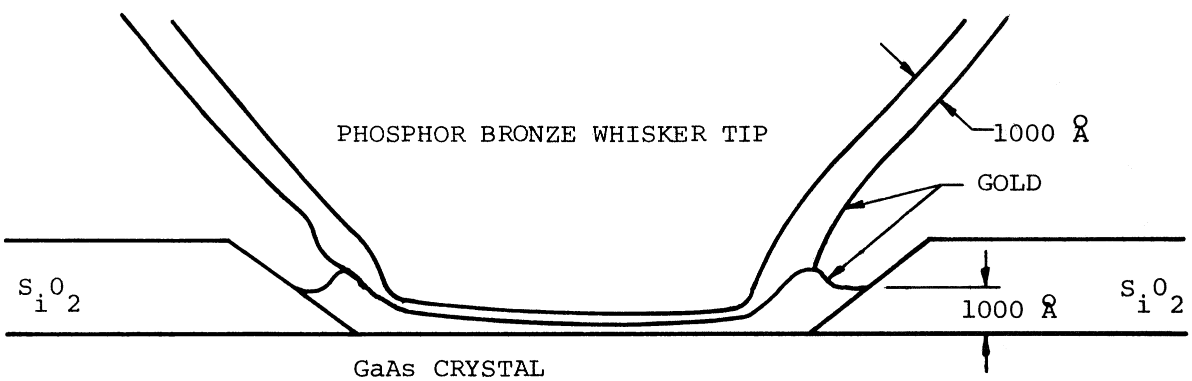

Figure 5. Plastically Deformed Whisker Tip

The estimated total amount of plastic deformation is about 2000 Å = 0.2 μm. This number could be arrived at through extensive calculation, but the estimate is probably accurate enough for present purposes.

When the plastic deformation is added to the other whisker retraction factors, a total whisker retraction of 1.31 to 1.44 μm is obtained. Within the accuracy of these calculations it is even possible that the whisker retraction exceeds the whisker deflection of 1.5 μm so that no bending of the quartz substrate need be hypothesized to explain the occurrence of diode open circuits upon cryogenic cooling. In any instance, the residual whisker deflection available for retaining diode electrical contact is reduced to the range of 600 to 2000 Å, a very small deflection indeed! It is understandable that under these circumstances any mechanical instability in the mounting of the diode that would permit or encourage bending or buckling of the quartz substrate would be a potential cause of diode failure. These effects are discussed in more detail in the next two sections.

3.6 Bending and Buckling of the Quartz Substrate

The forces required to produce bending or buckling deflections of the order estimated above may be calculated from straightforward mechanics considerations. For a pure bending force produced by moments applied to the ends of the quartz substrate, the deflection may be expressed as

$$\frac{d^2y}{dx^2} = \frac{d\theta}{dx} = \frac{1}{\rho} = \frac{M}{EI}$$

where:

- y is the vertical deflection
- θ is the angle of the substrate with respect to the x axis
- ρ is the radius of curvature of the bent substrate
- M is the bending moment
- E is Young's modulus for quartz
- I is the 2nd moment across the small dimension of the quartz

For quartz, $E \cong 10^7$ lb. in.$^{-2}$.

I calculate:

$$\rho\theta = \ell = 1.1 \times 10^{-2} \text{ in.}$$

$$\rho = 1.1 \times 10^{-2} \text{ in}/\theta \text{ rad}$$

$$\rho = 1.1 \text{ in for } \theta = 10^{-2} \text{ rad}$$

$$\rho = 11 \text{ in for } \theta = 10^{-3} \text{ rad}$$

The value of $\theta = 10^{-2}$ rad corresponds to a whisker retraction of the full 1.5 μm as originally calculated in section 3.2. $\theta = 10^{-3}$ rad corresponds to a whisker deflection of 0.15 μm which is more consonant with the estimate which considers the other sources of whisker retraction discussed above.

$$I = wt^3/12 = 3 \times 10^{-10} \text{ in}^4$$

$$M = \frac{EI}{\rho} = 2.7 \times 10^{-3} \text{ in lb } (\theta = 10^{-2} \text{ rad}) = M_1$$

$$M_2 = 2.7 \times 10^{-4} \text{ in lb } (\theta = 10^{-3} \text{ rad})$$

The lateral deflecting force required at the end of the choke (0.125 in lever arm) for these two bending moments is

$$F_1 = M_1/d = .0216 \text{ lb} = 9.8 \text{ gm}$$

$$F_2 = 0.98 \text{ gm}$$

This order of shear (transverse) force may be generated at the i.f. bellows end of the choke under cryogenic conditions such that free play develops for the i.f. center conductor as will be discussed later as the "oil-canning" effect.

The force required to buckle the quartz considered as a column may also be computed in a straightforward fashion. The Euler limit for buckling may be expressed as:

$$P_f/a = \pi^2 E/(L/r)^2$$

where a = cross section area of quartz

L = length of quartz

r = radius of gyration about buckling axis

$$r = \sqrt{I/a}$$

we have: $a = wt = 9.9 \times 10^{-5} \text{ in}^2$

$r = 1.73 \times 10^{-3}$ in

$L = 250 \times 10^{-3}$ in

$L/r = 144.3$ (within elastic buckling range)

$P_f = 0.469$ lb $= 213$ gm

This seems a rather high buckling force for such a slender quartz piece, but in any instance, must be compared with the axial loading force supplied by compression of the bellows located on the end of the i.f. center conductor.

The bellows deflection was originally not monitored as a routine procedure during mounting of the diode in the mixer block. Then, it was discovered that the deflection was quite large, up to 10 mils, in at least one instance. It appears that there is considerable variation in length between a new and used bellows. Also, the bellows are soft soldered onto the center conductor which probably allows a tolerance of ±2 to 3 mils. Since this discovery, the amount of bellows compression has been brought under control through the use of shims to adjust the outer conductor placement so as to obtain about 2 mils of bellows compression. The spring constant of the P/N 2510 electroformed bellows from Servometer Corporation is quoted as 0.22 oz. minimum for 12 mils deflection with a tolerance of +100%. This works out to between 0.5 to 1 gram per mil of bellows compression. At this rate, the axial force on the quartz would be only 1 to 2 grams for the present 2 mil deflection, and would have been only 5 to 10 grams for the maximum deflection observed of 10 mils. There is a strong likelihood that the spring constant of the bellows increases with deflection since the convolutions tend to bottom out against one another. However, it is difficult to imagine even approaching at force of 213 grams to produce buckling without completely crushing the bellows which is definitely not occurring.

3.7 "Oil Canning" of the I.F. Center Conductor

It must be realized that the i.f. center conductor plays a major role in loading and constraining the quartz diode-choke subassembly. The compressive axial force is transmitted from the bellows to a captured OSM-214 CC connector as shown in Figure 6.

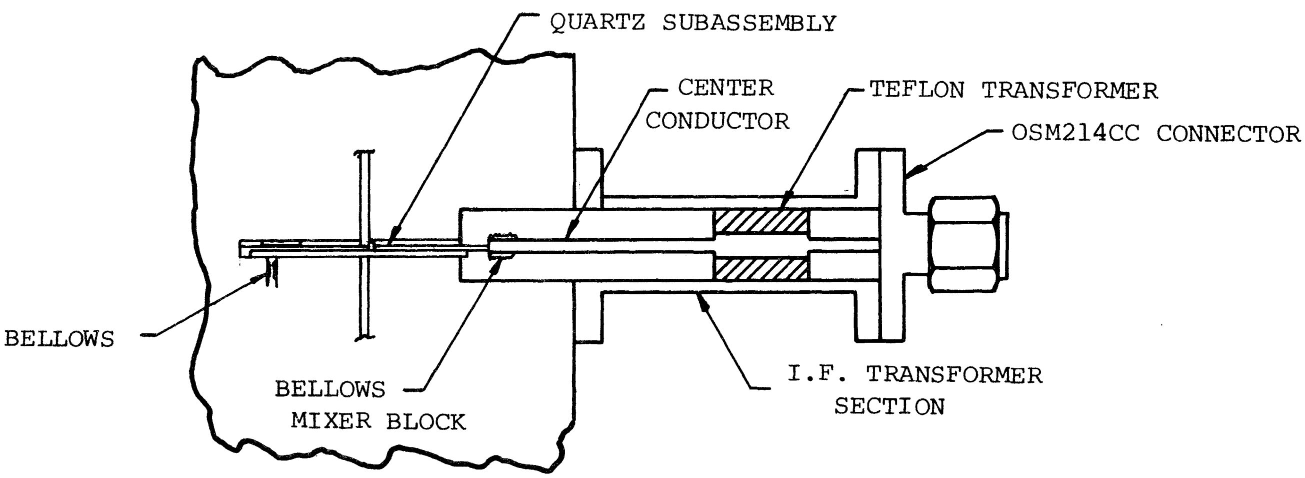

Figure 6. Sectional View of I.F. Transformer Section In Contact with Diode-Choke Subassembly

In particular, it should be noted that one mixer block with associated i.f. transformer section gave recurrent difficulty in attempts to cool diodes without producing open circuits. This mixer block was tried with 4 or 5 different diodes but always produced a failure. Subsequently, it was discovered that the teflon i.f. transformer was a much looser fit than usual for this unit so that, even at room temperature, there was some play in the center conductor. Upon replacing the teflon piece with one that gave a much snugger fit (the new piece was cooled to 77°K for insertion in the outer conductor) this mixer block cooled to 77°K without producing a diode open circuit.

It appears that upon cooling the teflon transformer contracts substantially thus allowing free play in the i.f. center conductor. Under these conditions, the center conductor "oil cans" over to one side or the other under the influence of the axial stress plus any other loads transmitted from the OSM connector. The amount of free movement available at the bellows-quartz location is substantial since this motion is magnified by the distance from the teflon transformer.

The lateral force available at the bellows to be transferred at the time "oil canning" of the center conductor occurs results from both the axial compressive force loading the bellows as well as any built in stress at the OSM connector that is being sustained by the teflon bushing. The axial force is of the order of 1.5 to 3 grams based on the previously discussed spring constant and a deflection of about 3.3 mils which includes 1.3 mil of differential contraction between the brass block and the quartz substrate. Since this force remains substantially along the axial direction, it is not believed that a lateral component of about 1 gram could be generated to provide the minimum bending force necessary to open circuit the diode. However, the unbalanced stress released by the shrinkage of the teflon bushing could easily generate a force this large. In other words, the lateral location of the i.f. center conductor at the bellows end is determined by the teflon bushing plus the direction the center conductor leaves the OSM connector in the free state. When the teflon bushing gives up its constraining action through shrinkage, the center conductor returns to the position determined by the way it leaves the connector. Under these circumstances, the lateral force available at the bellows end may easily be assumed to exceed 1 gram. The fact that teflon tends to cold flow under load implies that tightening this bushing at room temperature is a temporary solution to this problem and that a more permanent solution lies in a different choice of material and/or another means of constraining motion of the i.f. center conductor under cryogenic circumstances.

4.0 Summary of Remedies, Applied and Recommended

Two separate lists will be given to show those remedies that have been applied to improve the yield of coolable diodes for the 80-120 GHz in the recent past and to indicate areas where further changes may provide greatly increased diode service life and reliability. The remedies applied were done so on a piecemeal basis as the effects involved became better understood. It is the present intention to at least incorporate all these procedures and improvements into each existing mixer block as the diodes are replaced for the next time (all 8 mixer blocks are presently servicable with good diodes at the time of this writing).

A. Remedies Applied:

1. Be sure whiskers are fabricated from annealed phos. bronze wire and are properly pointed and plated.
2. Be sure the Eastman 910 cement is fresh and is setting up properly.
3. Minimize flexure of the quartz substrate in the whiskering jig. This fixture in its present condition is barely usable and should be replaced with a new design which eliminates flexure by fully supporting the quartz substrate.
4. Use the second assembly technique described for mounting the diode-choke assembly in the mixer block with particular attention paid to making the indium land flat and centering the quartz in the channel.
5. Accurately control the compression of the bellows on the i.f. center conductor to be 2 mils through the use of shims between the i.f. transformer section and the osm connector.
6. Use very snugly fitting teflon transformers (bushings) in the i.f. section to minimize free play in the center conductor. If possible shrink the teflon by cooling to 77°K prior to inserting in outer conductor. The teflon should be changed every time the diode is replaced since cold flow will cause an increase of clearance for this part.

B. Recommended Further Remedies:

1. Very accurate control of whisker pointing and gold plating thickness to minimize plastic deformation.

B. (continued)

2. Use of whisker deflection greater than 1.5 μm. (This must be approached with caution since 2.0 μm was tried and produced a punched through device upon cooling).
3. Change the whisker material to reduce contraction, try tungsten, molybdenum, tantalum, etc.
4. Change from quartz to thermally matched glass substrate to minimize differential contraction.
5. Change from teflon to another dielectric for i.f. transformer to eliminate cold flow and minimize dimensional change, try irradiated polypropylene.

5. Implications for Future Cryogenic Mixers

The implications for future cryogenic mixers are that intensive structural and thermal analysis needs doing before committing to a design with greatly reduced cross sectional area for the quartz substrate. The 150 GHz mixer is presently designed with a 3 mil thick quartz substrate of the same configuration discussed here to prevent moding problems. Since beam strength (resistance to flexure) varies as thickness cubed, it is it apparent that this substrate is already 8 times weaker than that of the 80 to 120 GHz mixer discussed here. In other words, only 1/8 gram transverse force might be required to open circuit the diode. For a 230 GHz mixer the problem is yet more severe. This needs to be looked at very closely. A different configuration for mounting the diode providing improved mechanical and thermal stability appears highly desirable.