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Indium-Barrier-Indium Tunneling Junctions

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We have successfully produced high quality In - Insulator - In tunnel junctions with resistances at 4°K varying over 12 orders of magnitude - from .01 ohms to .01 gigaohms.

Junction preparation involved the following new technique. An indium film was deposited onto a glass substrate held at liquid nitrogen temperature in a vacuum of 10^{-5}- 10^{-6} torr. After deposition the chamber was valved off and the sample gradually allowed to warm overnight to room temperature. The film was then placed in a reaction chamber consisting of a copper tube with two high voltage copper electrodes at one end and a roughing line and gas bleeding line at the other. The position of the sample relative to the electrodes was the critical factor in varying the resistance of these junctions. High impedance junctions faced toward the electrodes while low impedance junctions faced away. The vapor from a high molecular weight fluorocarbon liquid was continuously pumped through the chamber while a D.C. plasma discharge was maintained at pressures ranging from 300-750 microns for periods of 5 sec to a few minutes. Five cross strips of indium were then deposited at room temperature.

Junctions of the following three types were produced: 1.) intermediate junctions in the range 1-1000 ohms which exhibited pronounced structure in their dV^2/dI^2 characteristic reflecting the In phonon spectrum; 2.) low impedance junctions in the range .01 - 1 ohms which exhibited Josephson junction characteristics; 3.) high and ultra high junctions in the range 10,000 ohms - 10,000 megohms.

Intermediate Resistance Junctions

In addition to reproducing the general features of the phonon structure observed for aluminum-aluminum-oxide-indium junctions by various authors,[1-3] we have resolved additional fine structure throughout the region of indium acoustic phonon energies.

In Figure 1. we compare our raw second derivative data for an In-I-In junction at $.9^{\circ}$K with the data taken by J.M. Rowell and R.C. Dynes[2] for an Al-I-In junction taken at $.3^{\circ}$K. The main differences are fairly evident: a peak instead of a plateau at 7 mev (as measured from the energy gap $2\Delta_0$=1.05 mev); complex structure in the range 8-11 mev with a sharp dip at 9 mev ; broad humps beyond the longitudinal phonon peak at 14 mev. In addition we observed a small peak at 1.6 mev not shown on figure 1.

Most of these additional features can be related to structure in the phonon density of states. Recent neutron data by Smith and Reichardt[4] was interpreted using a Born von-Karman model to obtain the phonon spectrum for In. Their data indicates a saddle point at approximately 7 mev and a local maximum at 9 mev, corresponding to the peak at 7mev and the dip at 9 mev. in Fig. 1. The broad spectrum beyond the longitudinal peak is most likely attributable to sums and harmonics of the transverse and longitudinal peaks reflecting the phonon density of states at these higher energies.[5,6] The low energy peak at 1.6 mev does not reflect any appreciable structure in the constructed BvK spectrum.

These same intermediate junctions also clearly exhibit inelastic tunneling processes via excitation of vibrational modes of molecules in the barrier (Fig. 2) Peaks in the dI^2/dV^2 vs V characteristic indicate the onset of new tunneling processes at $V = 2\Delta_0 + \omega_b$ where ω_b is the energy of a vibrational or rotational mode of a barrier molecule. Peaks at 35 and 64 mev were recently observed by I.K. Yanson[7] who attributed them to phonons in InO which he indicated was the major component of the barrier for his In-I-In junctions. While we do not deny the possibility of some InO in our barrier, our evidence indicates that the major constituent of our barrier is compounds of In with C_nF_m type structures. Hence we attribute the peak at 62 mev not to InO but to In-C stretching modes which lie in the range ~ 58-71 mev for different molecular weight compounds.[8] We also note that InF has a sharp mode at 66 mev.[9] In addition, peaks corresponding to strong vibrational modes of C-F bonds are observed at 54 mev, 79 mev and 113 mev.[10]

Low Impedance Junctions

Junctions were also made which exhibited a Josephson current which could be nulled with a field of about 5 gauss. In zero field the maximum Josephson current for the best of these junctions was 87% of the theoretical result for the ideal superconductor $J_s^o = \frac{\pi\Delta_0}{2R_{NN}}$ However, the theory of McCumber[11] when used to calculate J_s including strong coupling effects gives J_s/J_s^o as .788 for Pb and .911 for Sn. Since the expected deviation of the tunneling density of states from the BCS theory is 5% for Pb, 1% for In and .5% for Sn,[12] the value $J_s/J_s^o = .87$ for In looks quite reasonable.

Fiske steps characteristic of self resonant junction modes were observed for many low impedance junctions. Using the theoretical expression for the step spacing[13] $V_{n+1} - V_n = \frac{hc}{4eL}\sqrt{\frac{t}{\epsilon}}$ (here ϵ is the barrier dielectric constant, L= width of junction, t = barrier thickness, λ = penetration depth of In taken as 640 A^0 and d= 2λ + t), we have obtained a value of t/ϵ = 2.4 A^0 for these low impedance junctions.

High Impedance Junctions

At the other extreme, we have made junctions whose resistance at 0 volts and 4^0K was at least 10^{10} ohms. A typical trace of the I-V characteristics of one of these junctions is shown in Fig. 3. Gap structure could not be resolved in this case possible because of leakage currents or noise. Note that in the region of the energy gap the total normal current is only 10^{-13} A. Junctions of a megohm or so did show gap structure with about 50% excess tunneling current and suprisingly showed some phonon structure at higher biases. Capacitance measurements were made and the capacitance of these junctions varied as the junction area. For a typical area of 3.3x 10^{-4} cm^2 we measured 100pf. This amounts to approximately .3 microfarads/cm^2. Interestingly enough the combination of high impedance and reasonable capacitance necessitated the I-V characteristic measurement at very slow sweep rates, since the junctions had an intrinsic RC relaxation time of about 1 sec. Using the expression $C = A\epsilon/t$ we obtained values of t/ϵ = 30 A^0 which is reassuringly larger than the value for the low impedance junctions. If we assume a typical bulk dielectric constant for an organic polymer like polyethylene or polytetrafluoroethylene,= 2 we obtain the values t= $5A^0$ for the low impedance junctions and t = 60 A^0 for the high impedance junctions. Attempts to fit these values in the W.K.B. approximation for the tunneling resistance using the expression ($R \propto$ $\exp 2\sqrt{\frac{2m\varphi_B}{\hbar^2}}\,t$ ~~[illegible]~~) resulted in a barrier height of approximately .25 ev. This is probably too low.

We note that unlike most high resistance junctions formed from oxides (and usually four orders of magnitude lower resistance) these junctions are very insensitive to transients and rather callous treatment

Conclusion

We have succeeded in producing tunneling junctions using a material, In, which is a "bad actor" as far as forming oxide barrier junctions.[2,7] We have observed much of the typical good tunneling junction characteristics and in the process obtained additional information concerning the In phonon density of states, and the effect of strong coupling on the magnitude of the Josephson current. In addition we have produced anomalously high resistance junctions which are physically very interesting and may very well have thin film circuitry applications. Studies are now under way applying our barrier production technique to the formation of junctions composed of other materials which cannot readily be utilized using conventional techniques.

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FIGURE CAPTIONS

Fig. 1. a) Second derivative trace taken from the McMillan, Rowell, and Dynes tabulation[3] for an Al-I-In junction at .3°K.

b) Second derivative trace made by the authors for an In-I-In junction at .9°K

Fig. 2. Second derivative trace for the same junction as in Fig. 1 Taken at 4.2° K using two modulation amplitudes.

Fig. 3. I-V characteristic of a very high impedance junction taken at 4.2°K.

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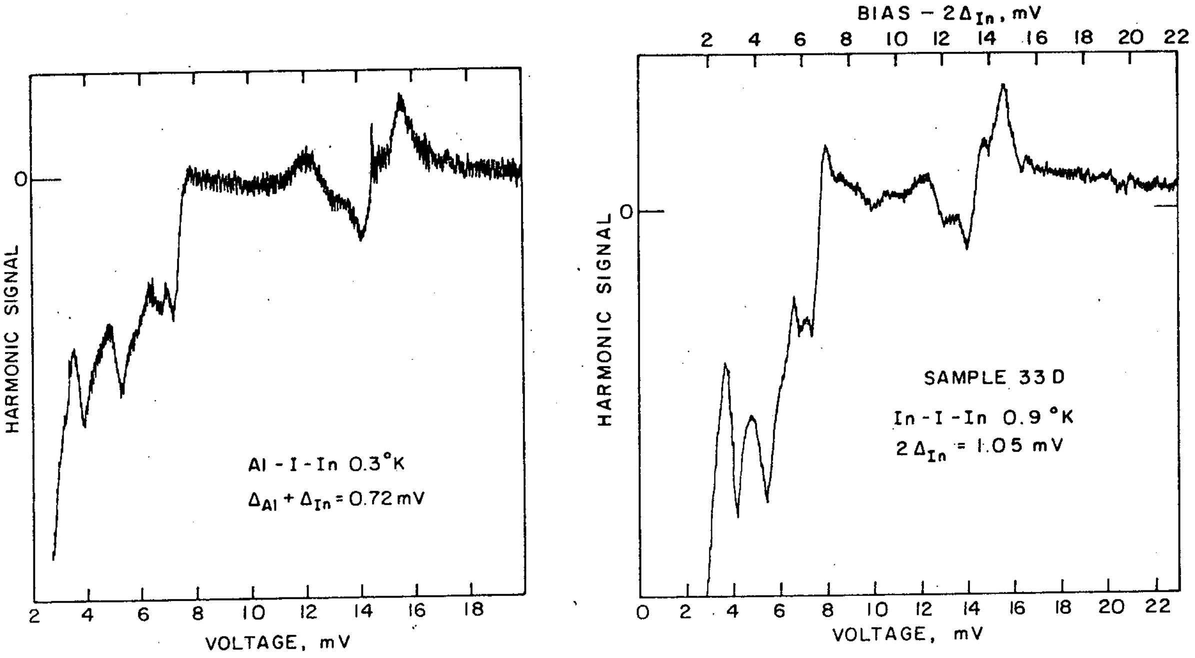
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Al - I - In 0.3°K
$\Delta_{Al} + \Delta_{In} = 0.72$ mV
2
4
6
8
10
12
14
16
18
VOLTAGE, mV
BIAS − $2\Delta_{In}$, mV
2
4
6
8
10
12
14
16
18
20
22
HARMONIC SIGNAL
0
SAMPLE 33 D
In - I - In 0.9 °K
$2\Delta_{In}$ = 1.05 mV
0
2
4
6
8
10
12
14
16
18
20
22
VOLTAGE, mV

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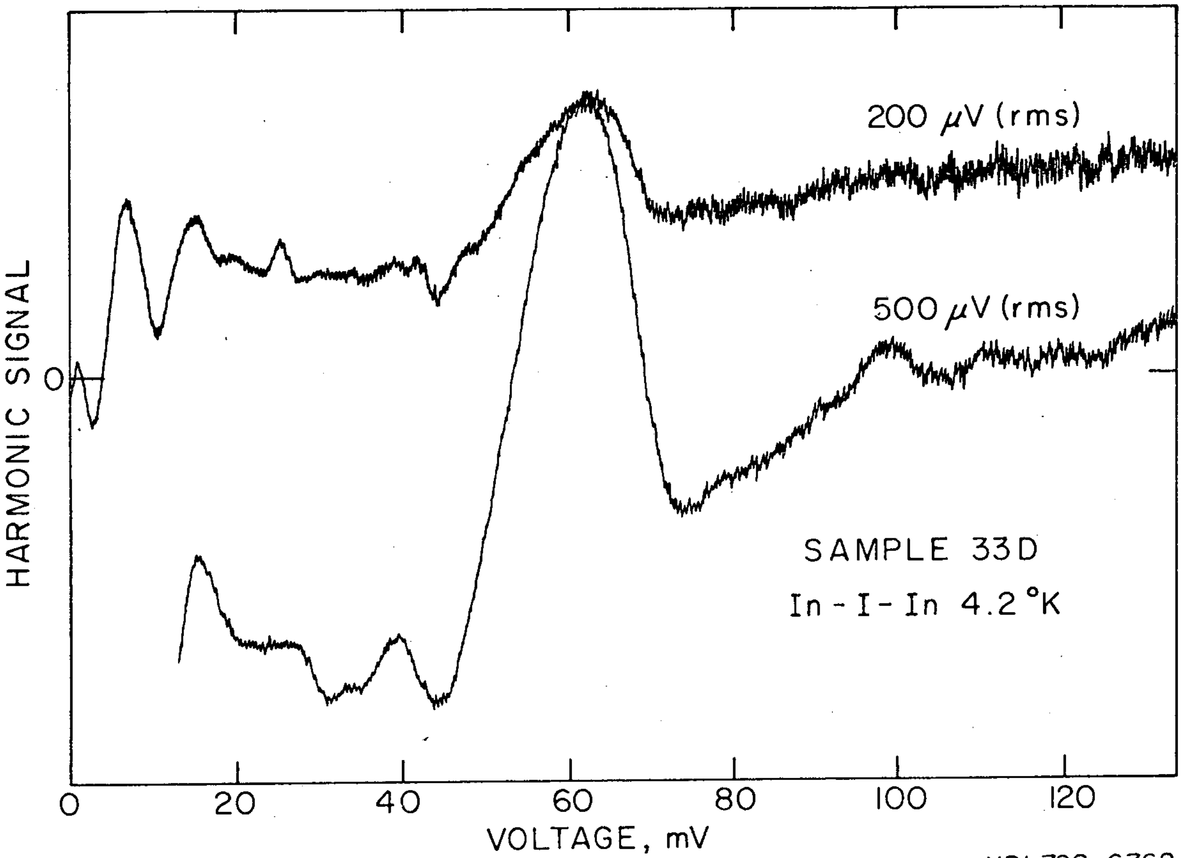
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500 μV (rms)
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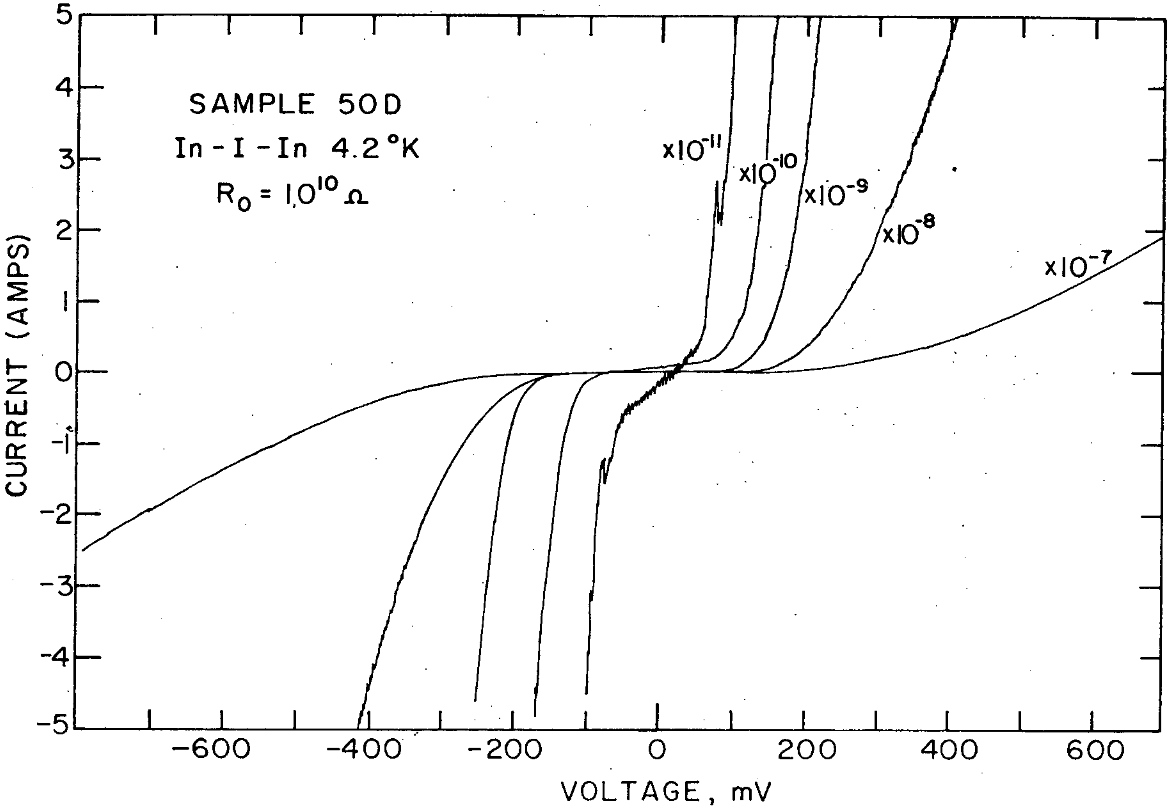
60
80
100
120

XBL728-6762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In-I-In 4.2°K
$R_0 = 1.0^{10}\,\Omega$
x10^{-11}
x10^{-10}
x10^{-9}
x10^{-8}
x10^{-7}
CURRENT (AMPS)
VOLTAGE, mV
5
4
3
2
1
0
-1
-2
-3
-4
-5
-600
-400
-200
0
200
400
600

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